The Dynamics of Interruptions in Engineering Project Task Execution

by

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ABSTRACT

The performance of engineering project organizations can be characterized generally by the organization's ability to deliver projects "on time", "under budget" and "right the first time". In industries where demand is very unpredictable it is not uncommon for organizations to operate with very "lean" project engineering staffs. Members of those engineering staffs are in very high demand by many other groups within the organization, leading to frequent interruptions. These interruptions can have significant impacts on productivity. Moreover, the productivity impacts often lead to degrading project cost and schedule performance, increased workload and stress, more mistakes, and ultimately contribute to the compromise of business cash flow and profit performance. Because of the dynamic complexity of the project task execution process and its relationship to the larger business goals, it is difficult to understand the real impacts of interruptions and devise effective policies to prevent the impacts from affecting performance adversely. Policies which appear to make sense in the short term may have long term repercussions that are not intuitive. Ultimately, the engineering staff and resource management leadership becomes the target of significant criticism.

This thesis provides an overview of the dynamic impacts of interruptions on engineering project task execution processes, and identifies system structures, policies, and behaviors that may contribute to the chronic inability of engineering organizations to deliver results "on time", "under budget" and "right the first time". A specific organization in the defense industry was selected for the contextual basis of this research. Interviews with stakeholders of the project execution process were conducted extensively. Major themes identified in the interview process were used, in conjunction with social network analysis techniques to provide guidance for development of a formal system dynamics model. Model simulation results are presented, with insights into the effects of interruptions on the larger business operations, as well as suggestions for further work.

Thesis Supervisor: Professor Nelson Repenning

Acknowledgements

I would like to thank my thesis advisor, Nelson Repenning, for his support in this thesis, help in developing the system dynamics model and expertise on project dynamics. His work in "firefighting" resonates with my personal experience in product development over the last decade. I would like to thank Peter Senge for writing the "Fifth Discipline" and the crisis of conscience that it provoked in me, leading ultimately to my discovery of the System Design and Management Program at MIT, and my renewed commitment to choose my professional destiny, lest it be thrust, unwillingly, upon me.

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1.0 INTRODUCTION

1.1 Background

"On time", "under budget", and "right the first time" are common refrains, heard in a wide variety of organizational settings. These phrases establish the fundamental goals of any delivery based process, regardless of whether it is a product or service to be delivered and whether it is to an external paying customer, or an internal customer in another division, or department. Functional engineering organizations often target schedule, cost, and quality as the most important indicators of performance. The simplicity and clarity of these goals often belie the challenges in approaching them, let alone achieving them. In the context of an organization responsible for the engineering of complex technical systems where long design and development cycles are common, and varying/uncertain market demand discourages resource staffing margins, it is particularly challenging. Engineers and managers alike have perennially struggled with these challenges.

Engineering design and development tasks for large and/or complex systems can be quite involved, requiring very long task execution durations, measured on the order of man-months to man-years of effort. In complex systems there is also a tendency for different tasks to be interrelated in series, concurrently, or iteratively. Maintaining high levels of focus on these tasks ensures productivity and quality output. If the task execution process is routinely interrupted, significant impacts to personal productivity of the engineers are incurred at a minimum. In small, highly capable engineering groups it is often the case that the engineers are connected multiply and recursively to other functions within the organization. As the "custodians of technical knowledge" they are relied upon heavily for a variety of tasks beyond the execution of project tasks for which they are directly accountable. At the technical epicenter of the organization, the potential for interruption is extremely high. Unfortunately, depending upon the policies chosen at the group/individual level to deal with these interruptions, a cascading effect can be seen through the entire organization resulting in delays, and cost overruns not only to the current development project, but also negative impacts to other development projects, production/delivery of products, service quality levels, marketing and sales campaigns, and ultimately business financial metrics such as cash flow, revenue and profit. Although there are many personal time management techniques available for reducing the impact of unnecessary interruptions, they are generally not sufficient to effectively handle, what are often necessary interruptions that are critical to the functioning of basic business processes.

In order to devise effective policies and procedures for addressing these necessary interruptions, limiting their negative impacts on not only the execution of project task work by the engineers, but through out the network of interrelated general business processes, it is imperative to gain an understanding of how the effects of interruptions cascade through the organization. At an abstract level, a business is a complex system. With multiple tightly coupled actors, interrelated processes that unfold over different time scales, adaptive responses to the external and internal environment promulgated through various policies and feedback mechanisms, a level of dynamic complexity exists that often makes it impossible to understand the behavior of the system and predict its response to any particular stimulus. “Common sense” will likely not succeed in achieving lasting positive results in such a context.

Various tools have been previously developed, specifically to address issues of dynamic complexity. Application of these tools can provide insight, and opportunity for real learning about the effects of interruptions of engineers on an extended organization. I have utilized a series of techniques that support the development of a formal system dynamics model of the system structure throughout which interruptions to engineering task execution may have impacts on the larger organization. The model, though limited in scope, provides valuable insights regarding how interruptions can affect project performance metrics as well as shape perceptions and strongly held mental models of engineers and managers alike.

1.2 Motivation & Objectives

In the last decade, I have personally witnessed the effects of interruptions to focused work and how they can cascade throughout broader business operations. The results have rarely been positive. Delays to, and errors in, long duration tasks in light of pressing near term interruptions tend to be the norm rather than the exception. In an industry and business climate where prolonged periods of surge capacity can have serious implications to competitive advantage, and "winning the next job", resource constraints are inevitable and despite a cacophony of pleas from every corner of the organization for more engineers, senior officers of the organization cannot, in good conscience and sound financial judgment, comply.

The inevitable result is the cultivation of a small, but highly capable and experienced technical workforce, whose "services" are constantly in demand. Firefighting is a way of life for all but the most specialized and insulated of engineering professionals. Despite the best efforts and intentions of engineers, supervisors, and managers, the negative impacts to budget, schedule, and the general technical capacity of the organization suffer more often than not. Moreover, the structure of the system itself somehow seems to contribute to the behaviors and resists the attempts to address the problems, leaving all with a feeling of helplessness, clinging only to our mental models shaped by the limited data we observe in our respective "corners" of the organization.

A broader perspective of the system in which we (engineers and non-engineers) encounter, resolve and learn about interruptions is sorely lacking. The professional life of an engineer can be both extremely rewarding, and at times extremely frustrating. My greatest frustrations as an engineer have been in dealing with the constant demands, and required multitasking, for which the only effective tool appears to be longer hours, greater stress levels, and a feeling that I am a "victim" of the system. In my discussions with colleagues, and classmates, and through the literature, I have come to understand that I am not alone, and that what may be missing is the "big picture" perspective which tries to see the larger system as an enactment of the players and processes of which it is comprised, creating behaviors which are understandable in the small, but beyond human comprehension in the "large."

If the tools, teachings, attitudes and behaviors to which I have been exposed in the System Design and Management Program at MIT, can be effectively used to understand the broad ramifications of interruptions, then the potential exists for organizations to make meaningful and lasting improvements in its business processes. This will further the goals of achieving higher revenues and profits, sustainable cash flows, and fostering healthier, more informed mental models throughout the organization. It is this constellation of factors that motivate the current research and its objectives.

The objectives of this research are:

1. To develop a formal system dynamics simulation model to examine the effects of interruptions of engineering project task execution processes
2. To develop a better understanding of the means by which these interruptions cascade throughout the broader organization

3. To identify any key interrelationships and feedback structures that play a significant role in generating the dynamics associated with interruptions.
4. To summarize insights derived from this body of research and potential policy implications for reducing the broad negative impact of interruptions.

1.2 Approach

The following provides a summary of the methodology followed to conduct the current research and meet its objectives. In addition, a general outline of the structure of the thesis is provided as a guide to various phases of the research effort and where they are documented within this thesis.

1.2.1 Methodology

The general methodology followed to conduct the current research and meet its objectives is summarized in the flow chart depicted in Figure 1 below.

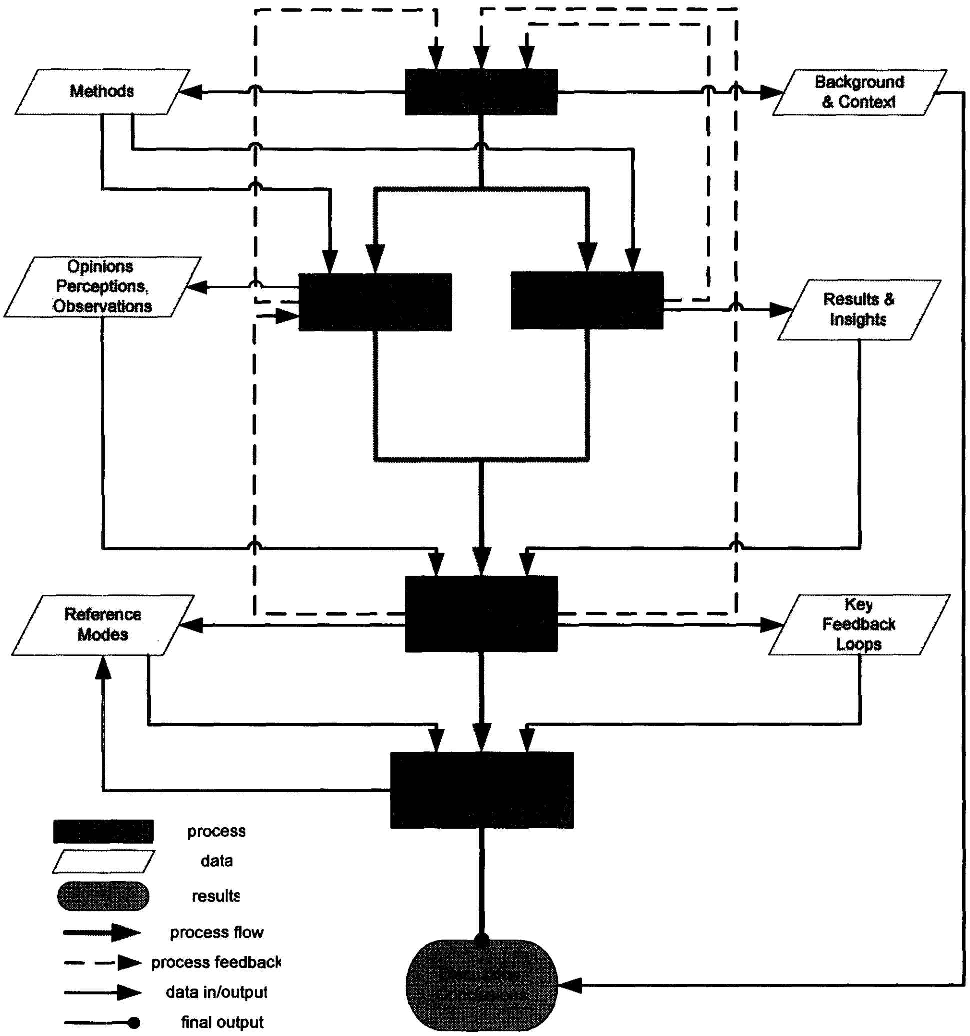

Figure 1. Research Methodology Flowchart

The diagram, while specific to the methodology employed for this research is representative of the typical recursive nature of any research process whereby data, observations, knowledge, etc. obtained in any step provides periodic cause for reevaluation of and return to previous steps to better meet the objectives of the research. Details of individual processes and the use of associated outputs are outlined in a later chapter. Locations of specific sections, within this document, that describe literature reviews, methods, discussion, etc. are identified in the subchapter immediately following.

1.2.2 Structure of Thesis

A comprehensive literature review is presented in Chapter 2 of this document. The chapter is subdivided into 5 sub-chapters that explore previous work in the areas of interruption studies, project task execution dynamics, social network analysis methods, and system dynamics modeling techniques.

Chapter 3 of this document describes the context and setting in which the current research has been completed. Descriptions of the industry and the specific organization that was used as a source of data/information are provided. In addition, the organization divisional structure, and its evolution are described. Finally I present an overview of the resource constrained environment in which the engineering staff execute project tasks and encounter and resolve interruptions.

Chapter 4 provides a summary of the various research methods employed to meet the objectives of this research. The extent and character of the interview process will be presented as well as a description of the network analysis techniques employed. This chapter concludes with a discussion of causal loop diagramming, and system dynamics modeling processes with simplified examples drawn from the early phases of the completed research.

Chapter 5 summarizes the results of the various research tools employed. Observations drawn from the interviewing process, categorized by major themes, will be presented in this chapter. Results of adjacency matrix manipulations will be provided as well. Themes and dynamic hypotheses derived from the interviews and network analysis results will be enumerated and their linkages to the causal loop diagramming process will be described. Results of the causal loop diagramming efforts will also be summarized. Finally, the formal system dynamics model that was developed will be described and output from the exercised model will be presented.

Chapter 6 will present a discussion of the results of this research. Chapter 7 will provide recommendations for extensions to this research, as well as other research areas suggested by this research. Chapter 8 will briefly summarize the conclusions of this research and Chapter 9 contains a listing of references. Appendix A contains documentation of the formal system dynamics model developed in the Vensim© modeling environment/syntax.

2.0 LITERATURE REVIEW

Interruptions and the impacts they have on individuals engaged in complex cognitive tasks has received much attention in the past. The contexts are quite varied, from the effect of email (Jackson 2001) and phone calls (Eyrolle 2000) on the productivity of workers in office environments, to air traffic control operators(Miller 2001; Ho 2004) and pilots(Dismukes 2003) sifting through information provided on tracking screens and displays, to time studies of software engineers (Perlow 1999), to effective interruption management (Seshadri 2001; Hudson 2002) and the value of interruption mediators(Dabbish 2003). Much of the recent literature focuses on the cognitive effects of interruptions, and how timing, preparation, and various other factors influence the ability to "recover" from interruptions(Altmann 2002; Adamczyk 2004). Several studies attempt to classify interruptions in categories such as intrusions, breaks, distractions, and discrepancies(Jett 2003), while others address lack of interruptions in work with a highly interactive component as problematic as well(Perlow 1999).

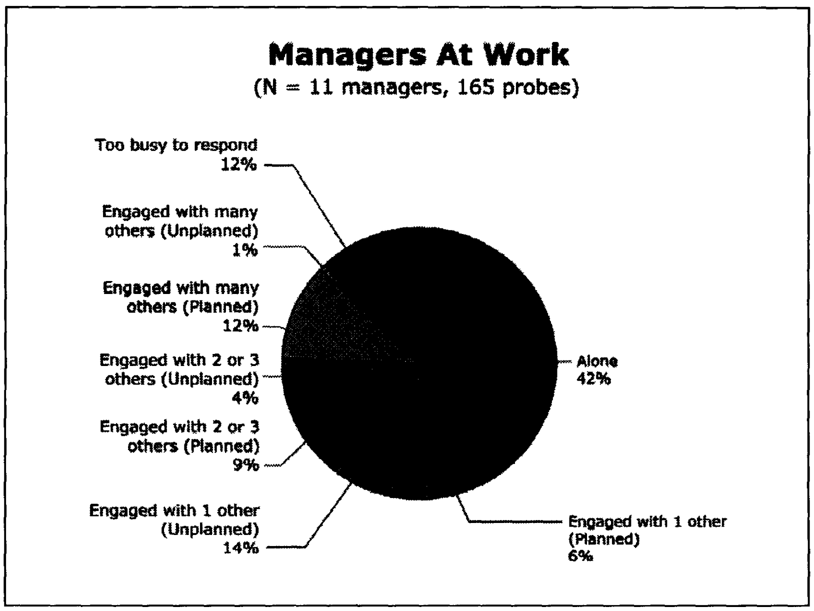

Figure 2. Management Availability and Interruption(Hudson 2002)

Type of interruption	Negative Consequences for the Person being Interrupted	Positive Consequences for the Person being Interrupted
INTRUSION	Insufficient time to perform time-sensitive tasks, stress and anxiety associated with heightened feelings of time pressure, and/or a disruption in a person's state of total involvement in the task being performed	Informal feedback and information sharing that is unlikely to occur though other, more established means
BREAK	Procrastination (i.e., excessive delays in starting or continuing work on a task) and/or significant amounts of time spent relearning essential details of the work being performed	Alleviation of fatigue or distress, a rhythm and pace of work that enhances job satisfaction and performance, and/or opportunities for incubation of ideas on creative tasks
DISTRACTION	Mediocre performance when the person's work is complex, demanding, and requires learning and one's full attention, and/or when the person has particular traits that make him or her more vulnerable or sensitive to distractions (e.g., lack of stimulus screening capabilities or a Type A personality)	Enhanced performance when the distraction helps filter out other irritating environmental stimuli and/or increases stimulation levels on routine tasks
DISCREPANCY	An intense, paralyzing negative emotional reaction, or continuous automatic processing of task-related information, if the discrepancy is suppressed or denied	Mindful, effortful, and controlled processing of information, and/or the recognition of the need for change and stimulation of action

Figure 3. Interruption Categorization (Jett 2003)

In much of the research on interruptions, the focus is on the individual, and how individual actions and policies can be devised to address them more efficiently. Time management experts continue to promote or develop software tools(Rodenstein 1999; Garai 2004), techniques, devices(CubeSmartInc. 2002) and "checklists" (Garai 2004)intended to alleviate the negative effects of interruptions in the workplace. A number of commercially successful management books promote the virtues of individual time management practices as keys to success in the workplace (Brooks 1989; Covey 1989; Covey 1994; Griessman 1994).

Though written recently, much of the advice is reminiscent of the early scientific management studies(Taylor 1911). Relatively few studies have attempted to evaluate how potential responses to interruptions effect the broader organization where social interactions, and thus interruptions, are frequent and critical to the primary function of the organization.

Activity Sheet 1: What's your hole made of?

Use the table below to log your interruptions over a few days or a week and then analyse your results to find out what is taking up so much of your time. Make as many copies of the table as you need. In each case note down the length of time of the interruption in minutes and initial each entry with a W for waste or a V for valuable and then for each day note down the total time taken up in each case.

Interruptions log for Date:									Total of hours worked for the day:							
Hour	Face to face					Telephone					Email					Other
	Boss	Colleagues/ staff	Customers	Friends/ family	Other	Boss	Colleagues/ staff	Customers	Friends/ family	Other	Boss	Colleagues/ staff	Customers	Friends/ family	Other	
07h00																
08h00																
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Total for W																
Total for V																

Figure 4. Personal Time Study Worksheet (Garai 2004)

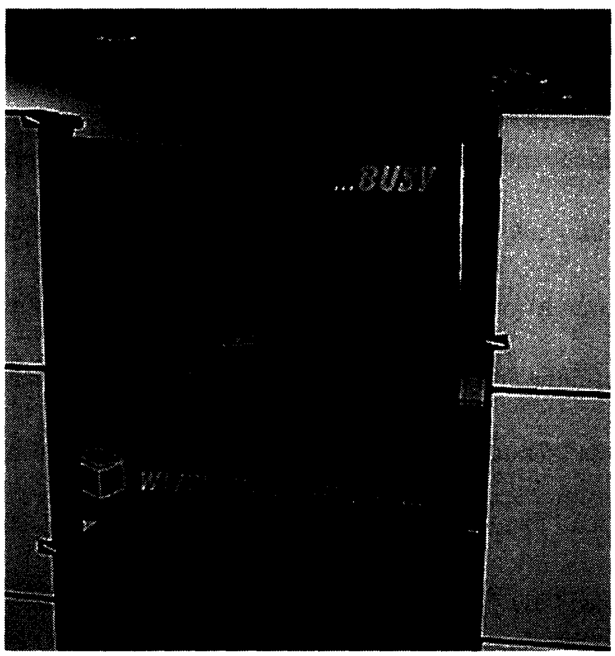


Figure 5. Personal Interruption Management Device(CubeSmartInc. 2002)

The degree to which engineering is "connected" to the other functions group within a business dependent to a large degree upon the complexity of the products and services, and the distribution of technical knowledge throughout the organization. Many methods exist within the field of social network analysis to assess the degrees of "connectedness", "dependency" and "reciprocity" between actors in a network. Directed graphs and the adjacency matrices derived from them are common tools available for making such assessments (Hanneman 2001). The adjacency matrix in particular has demonstrated its value in many contexts from design task interrelationships, to product architectures and work team design (Eppinger 1994). Simple matrix manipulations (e.g. inverse, transpose, multiplication, etc.) can suggest the likelihood and degree of interruption potential within a network, based on the amount of concurrent and iterative work execution that is involved.

	Bob	Carol	Ted	Alice
Bob	---	1	1	0
Carol	0	---	1	0
Ted	1	1	---	1
Alice	0	0	1	---

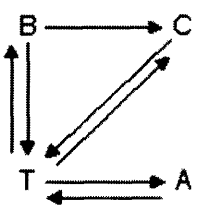


Figure 6. Adjacency Matrix and Directed Graph Example (Hanneman 2001)

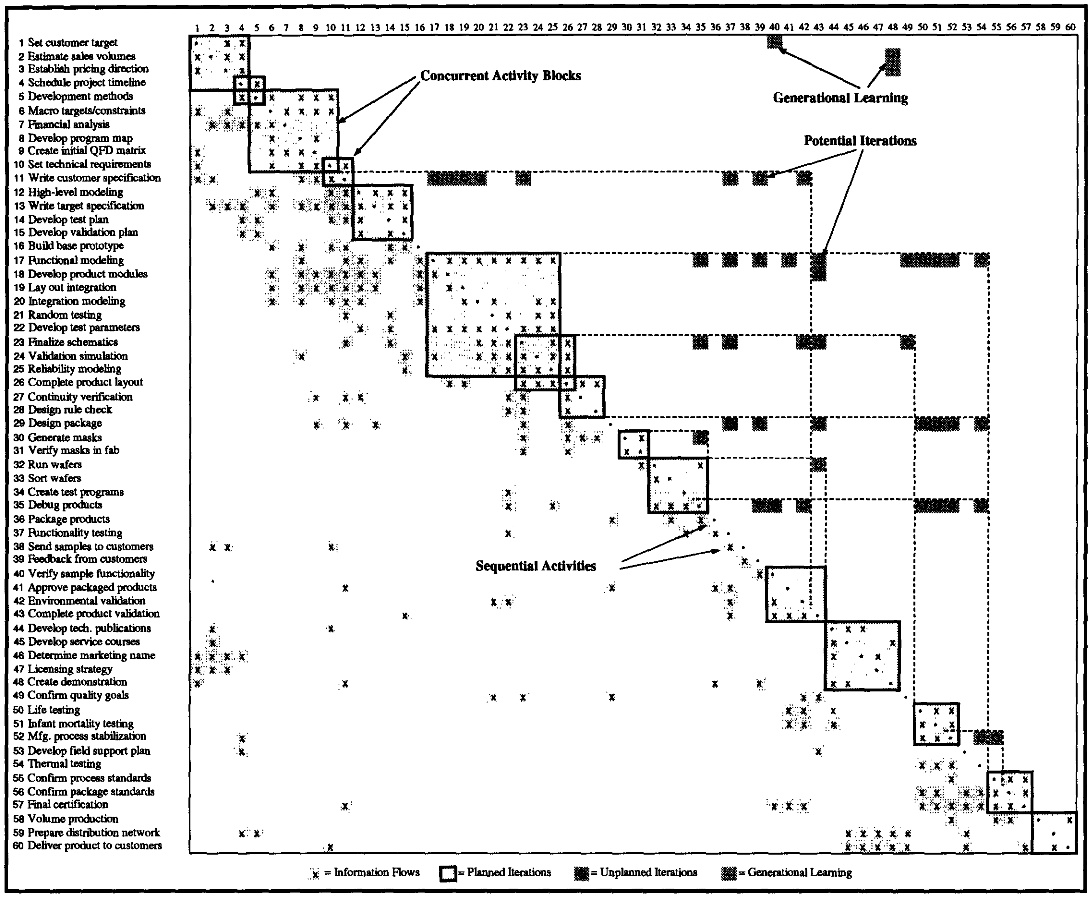


Figure 7. Semiconductor Development: Design Structure Matrix Example (Eppinger 2003)

The project task execution processes that are the focus of the current research are akin to a large body of research in the areas of product development, product development processes, and the unique challenges associated with development of complex technical systems. Some of the most difficult challenges often do not involve technology, but rather the confusing array of multiple demands, short term fire drills, shifting priorities, and interruption of focus for the engineering resources themselves. Since these factors typically arise from the social interactions between engineering resources and the other agents inside and outside the organization with whom they interact, the resulting behavior of the system is also quite complex, with cause and effect multiply linked, and not very amenable to understanding. This recognition has existed for some time, and several tools and methods have been applied to facilitate learning about such systems. System dynamics modeling, also used in the current research, is one such tool.

The field of System Dynamics was founded by Jay W. Forrester at the MIT Sloan School of Business. In his book “Industrial Dynamics” (Forrester 1961) he described how basic principles of control theory, common in his own field of electrical engineering could be used to model the behavior of non-technical dynamic social systems. Further, the linkages between engineering and management, and the system structure which was enacted by the two was ultimately responsible for the behavior of the system good or bad (Forrester 1964).

Many others have contributed to the field since its inception, and the tools and methods of system dynamics have been used to address a large number of complex social issues from urban renewal/decay, to disease epidemics, to the diffusion of new products in the market place, to interactions in supply chains, to project execution and management, and many, many others.(Sterman 2000; Lyneis 2001; Rudolph 2002; MacInnis 2004)

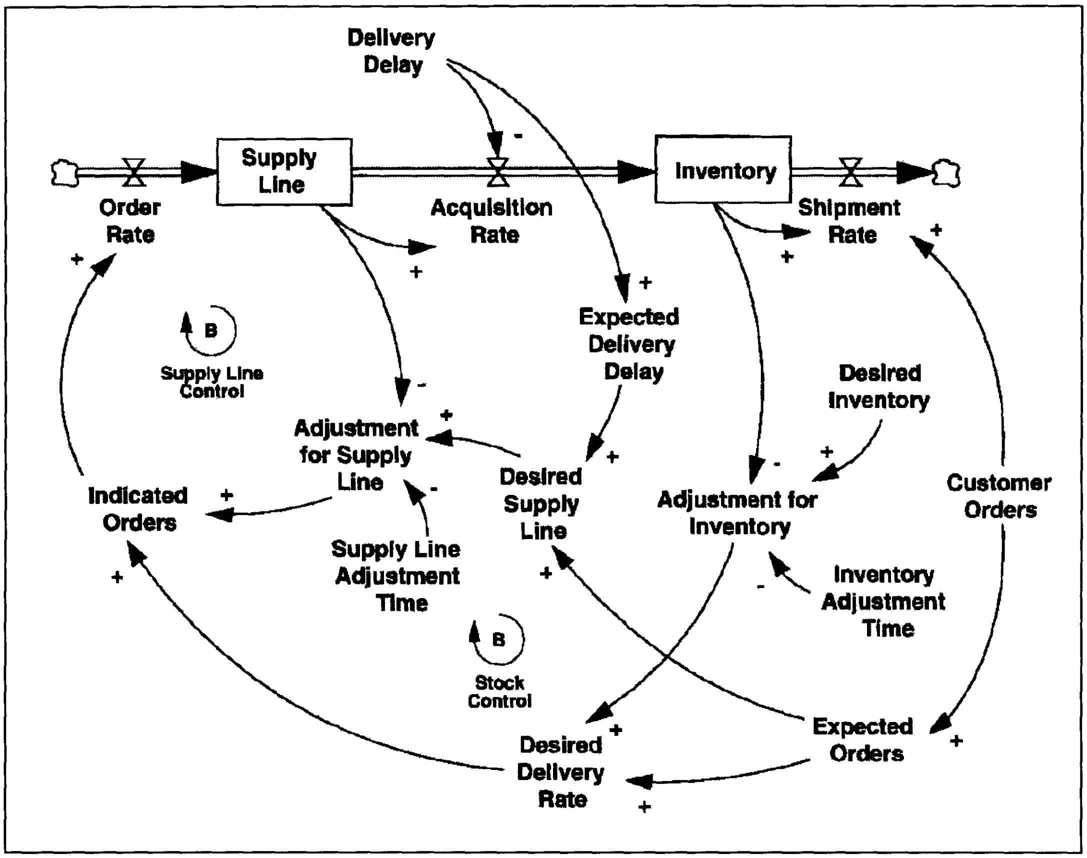


Figure 8. Beer Distribution Game Model(Sterman 2000)

The current research utilizes portions of the project execution and management models that have been developed previously. Specifically, the “rework model”, the kernel of the work execution model shown in Figure 9 below, has been adapted for use in addressing the impacts of interruptions to engineering staffing in the current research. In its original form, the model attempts to make explicit the effect of resource (de)allocation policies, and management behaviors in response to perceived measures of project performance. Based on perceived progress, management behavior will dictate how resources grow and shrink over time and how perceived progress influences the degree to which overtime and schedule pressure are applied. These factors can have profound implication on productivity and quality, which in turn moderate the rate at which work is executed, and the rate at which errors occur, mandating rework. The current research relies upon the same basic framework for project execution, but removes the "controls" over staff levels, while adding interruption resolution behavior policies.

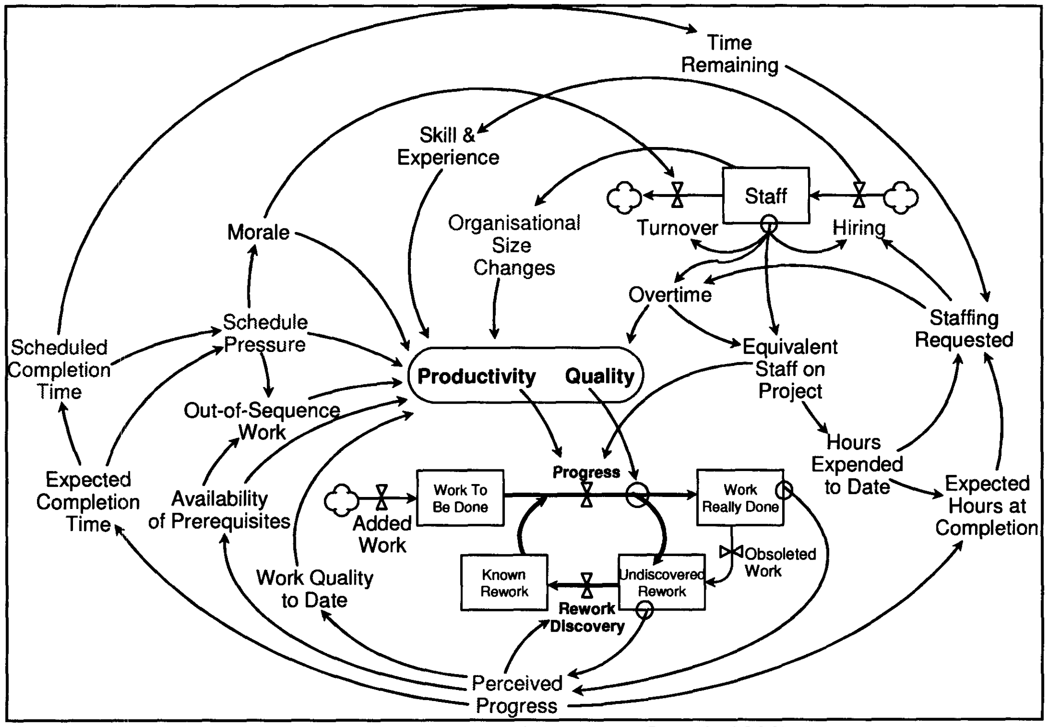


Figure 9. Work Execution Model(Lyneis 2003)

3.0 SETTING

The context in which this research was conducted can be described at various levels of abstraction from industry type to corporate/divisional structure, product/project complexity, and interpersonal working relationships. Each level provides information about the environment, policies, and behaviors which are exhibited amongst stakeholders of the many project task execution processes. This context was drawn from a single company at which I have been employed for the last decade as a member of the engineering functional group, starting as a junior entry level design engineer and currently a senior design/development engineer whose responsibilities include oversight and management of engineering resources, as well as project management responsibilities for funded research and development activities.

The company that was used as case study for this work is a large, global corporation with several primary business sectors. The business sector in which I have been employed is further divided into commercial and military divisions. I work for the military division designing and manufacturing maritime propulsion equipment and systems for U.S. Government applications within the Department of Defense (e.g. U.S. Navy, U.S. Marine Corps.) and Department of Homeland Security (e.g. U.S. Coast Guard). When I first joined this division it was a stand alone business, part of a privately held conglomerate of industrial and technology companies. The business, at that time, was focused around a handful of products that were sold through major defense system integrators (e.g. Northrup-Grumman, General Dynamics, Lockheed, etc.) for U.S. Government applications. At the turn of the millennium, several successive acquisitions of the company were made resulting in consolidation of the business as a division within a much larger global organization in which many different, yet related products and services could be offered for a much wider variety of commercial and military applications. The group underwent several years of transition in which significant change transpired including rationalization of products and customer bases, modifications in organizational design and reporting structures, influx of new management personnel, and integration of common corporate practices/procedures. This rapid change occurred concurrently with, and in response to a growth in the external market for old as well as new products and services. This growth continues today and is driven by the current "up-turn" in U.S. defense acquisition spending profiles, and the availability of new technologies and products from the business.

Historically, U.S. defense acquisition spending profiles have varied with a long period of oscillation that is modulated by factors such as political cycles, market cycles, budget deficits, perceived threats, and precipitating world events. Depending on the particular service within D.O.D., the operational life of equipment can be 25 years, and up to 40 years in the case of main machinery on board ships. The size and age of various classes of vessels within the Naval and Coast Guard fleet may also play a role in spending profiles as major assets become somewhat "long in the tooth" and new platforms roll off the drawing boards. With the long operational life of the vessels, aftermarket parts, repair, and overhaul become very important needs of the operator and a steady source of revenue for those businesses engaged in providing those services. This company has positioned itself to provide exactly these services in order to benefit from the large installed base of "class standard" equipment, and more importantly to maintain revenues and cash flows during the long "down-turns" which are part of the natural rhythm of the industry.

The products historically provided by this division can be characterized as complex and highly customized, manufactured in low-quantities. Many of the products have lower cost and capability counterparts in the commercial divisions of the company, but the products designed, manufactured, serviced, and refurbished by this division are products which were designed for a specific platform, subject to stringent and exacting requirements and specifications to withstand the rigors of military combat and provide capabilities specialized for military operational effectiveness.

The strategic design of the organization has evolved from a purely functional form to a matrix organization and, most currently, to an integrated project/product team environment. A high level depiction of the organizational structure changes that have occurred over the last several years is depicted below in Figures 10, 11, & 12. The evolutionary trajectory of the organizational design is consistent with other industries and organizations in which the number of offered products and services is growing due to industry consolidation and a commensurate increase in complexity of operations.

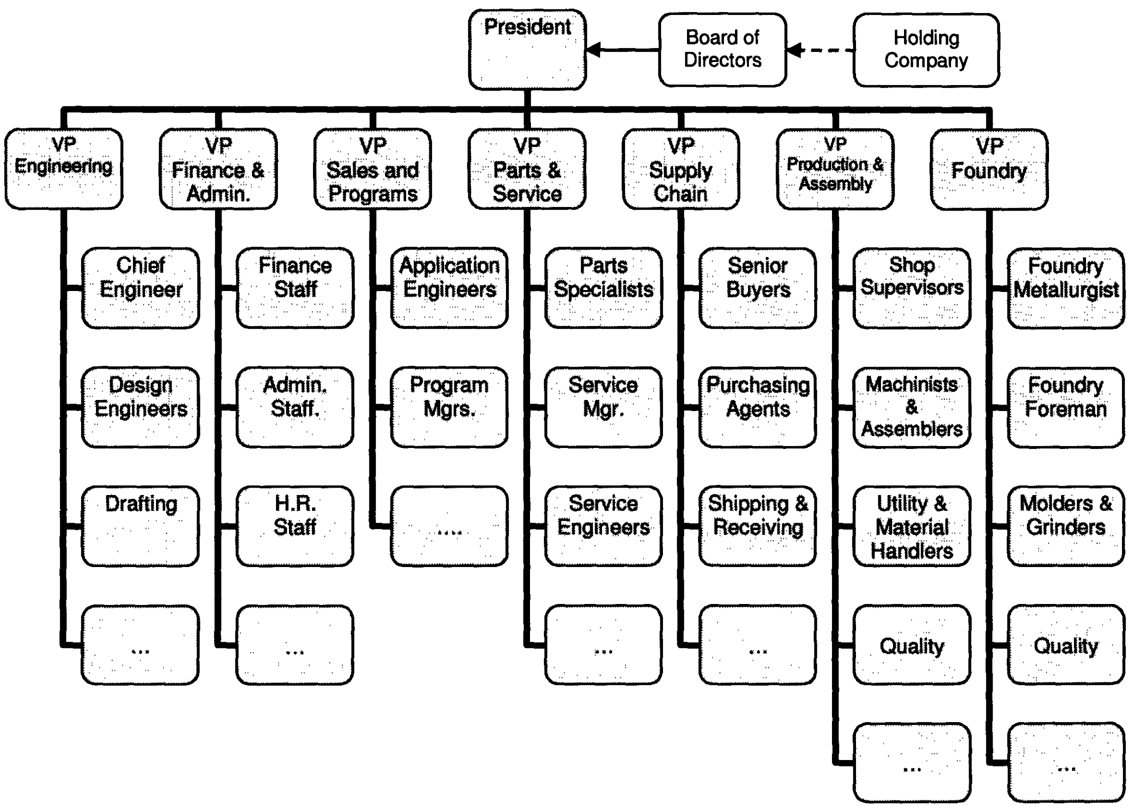


Figure 10. Functional Organization (1996)

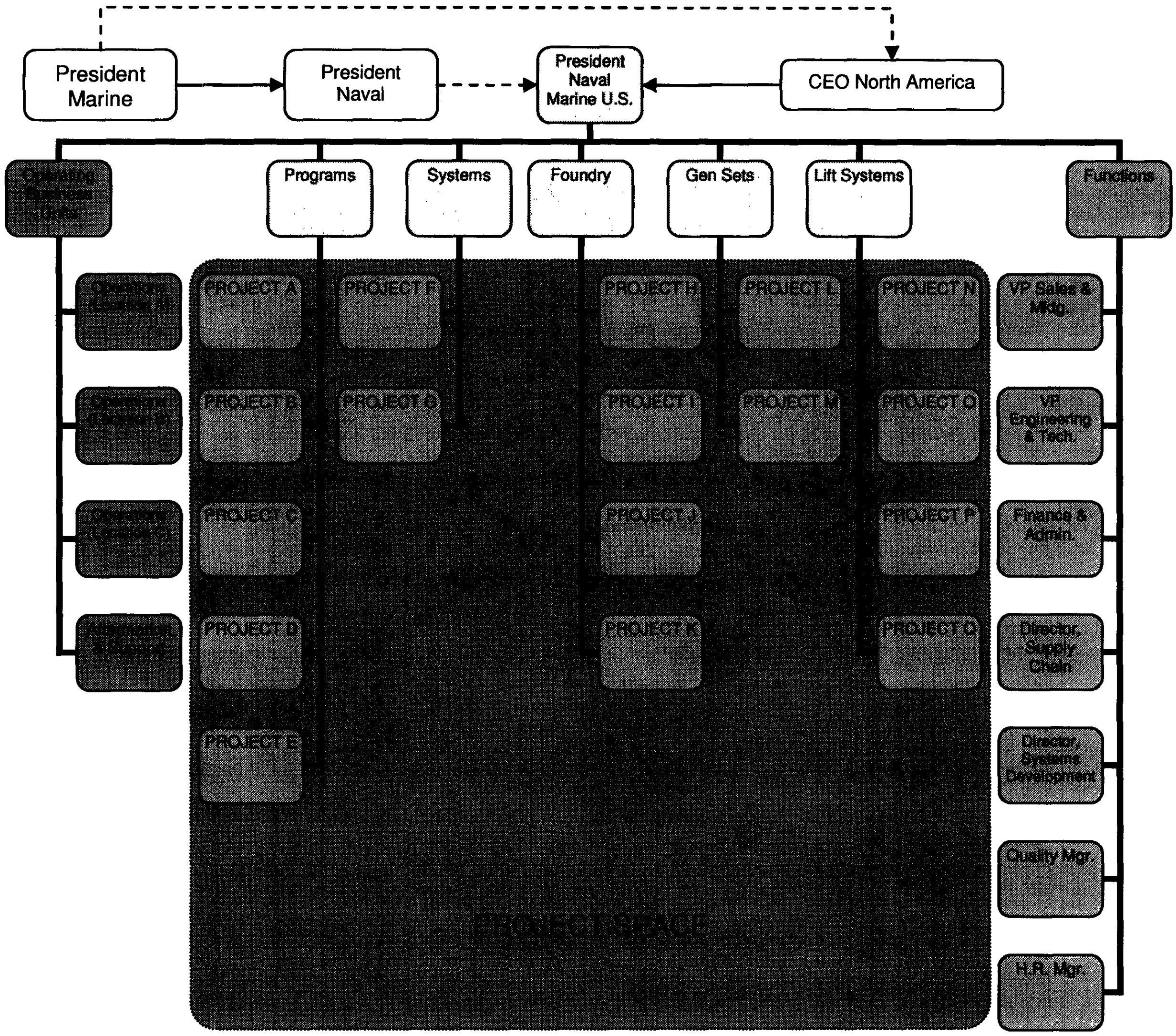


Figure 11. Matrix Organization (2003)

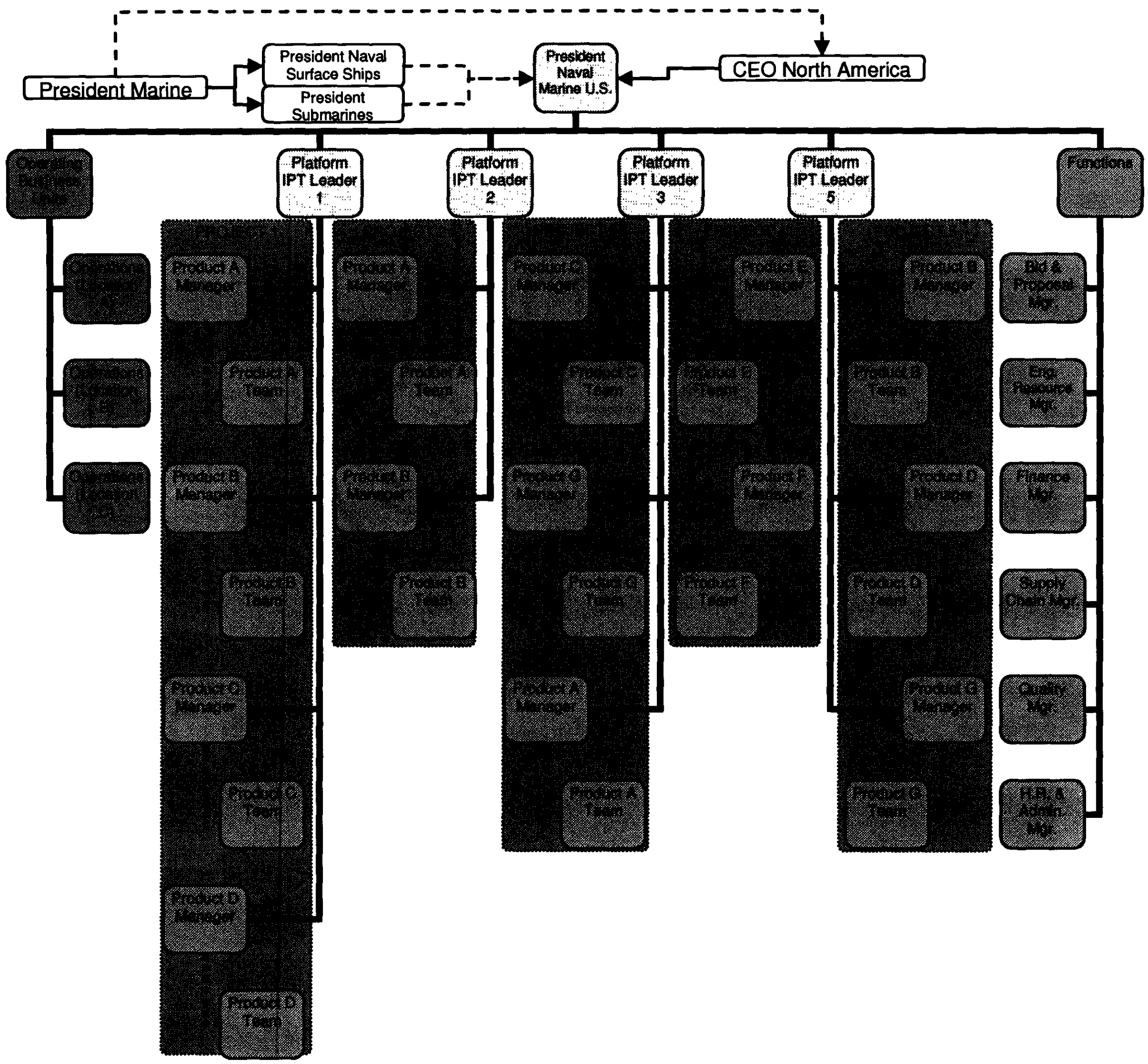


Figure 12. Integrated Project and Product Teams (2005)

Growth, although desirable in the aggregate, comes not without significant challenges in a resource constrained environment. The business division which is the context of this research operates with a very "lean" resource profile. That is to say, there is a relatively limited number of versatile and experienced staff responsible for the execution of project tasks, most especially in the engineering disciplines. Due to the cyclical and uncertain nature of U.S. defense acquisition spending, there is a justifiable reluctance to maintain high staff levels, or to engage in rapid hiring and firing, with significant instability in staffing levels. The result is a small, flexible, highly experienced, permanent engineering staff that is augmented, when possible, with outside support from temporary or contract engineering/drafting support. Due to the long life-cycles associated with products and services provided for shipboard applications, there is a significant technical body of knowledge which is relevant in production and aftermarket as well as in the up-front engineering and design phases. Historically, the organization has come to rely upon this small engineering staff to preserve that technical body of knowledge and leverage it when required to make important decisions about products and processes to address concerns of performance, and quality as well as project financial results and customer satisfaction.

The inevitable effect is that a small, highly networked group of individuals within an organization, despite being "allocated" to project/product teams, still must address the needs of the purely functional organization and must contend with a myriad of interruptions and requests for support from every corner of the business. It is the dynamics of these interactions that are the subject of this research. The chapter that follows will describe the methods used in which to characterize the engineering staff network within the organization, and the problems that have arisen historically as a result of the structure and behavior of the system and environment enacted by the same said staff.

4.0 METHODS

This chapter details the methods used to achieve the thesis objectives. It includes a description of the interviews, network analyses, causal loop diagramming, and system dynamics modeling that were conducted as part of this research. Data and analysis results from the use of these methods will be provided in the results section of this document.

4.1 Interviews

A series of informal/unstructured interviews were conducted in groups and with selected individuals throughout the organization. The group interviews were conducted as "round-table" discussions wherein I served as the moderator. The purpose of the interviews was to obtain an understanding of the most troublesome issues involving engineering project task execution, and opinions and perceptions as to causes of those issues. The groups (and their compositions) and individuals interviewed are listed below in Table 1. The interviews were conducted prior to the transition to the current project/product IPT organizational design. Follow up interviews (mostly one-on-one) were conducted with some of the participants to clarify or augment observations, and statements made during the interviewing process.

Interview	Group / Individual	Composition
1	Engineering Staff	Chief Engineer, Design Staff, Drafting Staff
2	Program Mgmt. Staff	VP Programs, Program Managers
3	VP Engineering & Technology	(one-on-one)
4	Chief Engineer	(one-on-one)
5	Director, Operations (Location A)	(one-on-one)
6	Director, Supply Chain	(one-on-one)
7	Program Mgr.	(one-on-one)
8	VP Programs	(one-on-one)
9	Quality Mgr.	(one-on-one)
10	Support Mgr.	(one-on-one)
11	VP Finance	(one-on-one)
12	Director, Systems Development	(one-on-one)
13	President Naval Marine U.S.	(one-on-one)

Table 1. Interview Matrix

An attempt was made to solicit input from the primary stakeholders (Programs & Engineering) of the engineering task execution process in both group and individual interviews. The group settings provide a rich atmosphere for dialogue, brainstorming, and reactions to various comments made generating new observations, and related effects. The individual interviews provided an opportunity to solicit personal observations in a non-threatening (no managers or subordinates) atmosphere.

At each initial gathering, the discussion was opened through means of asking the interviewees to complete either of the following two questions with short phrases:

"The problem with engineering is……"

"The problem with engineering's role in the organization is….."

Based on the responses and ensuing discussion, follow up questions were asked to "flesh-out" those items which appeared to resonate most significantly with the groups or individual being interviewed.

4.2 Network Analysis

A simple network analysis was conducted to quantitatively and qualitatively assess the linkages that exist within the organization. Of particular focus are the relationships that exist between the engineering resources and the rest of the organization in the context of project task execution. A typical evolutionary profile for a project was developed based on personal experience over several past projects. An abstraction of the project execution process is depicted in Figure 13 below, with the principal phases, participants, and cash input points identified.

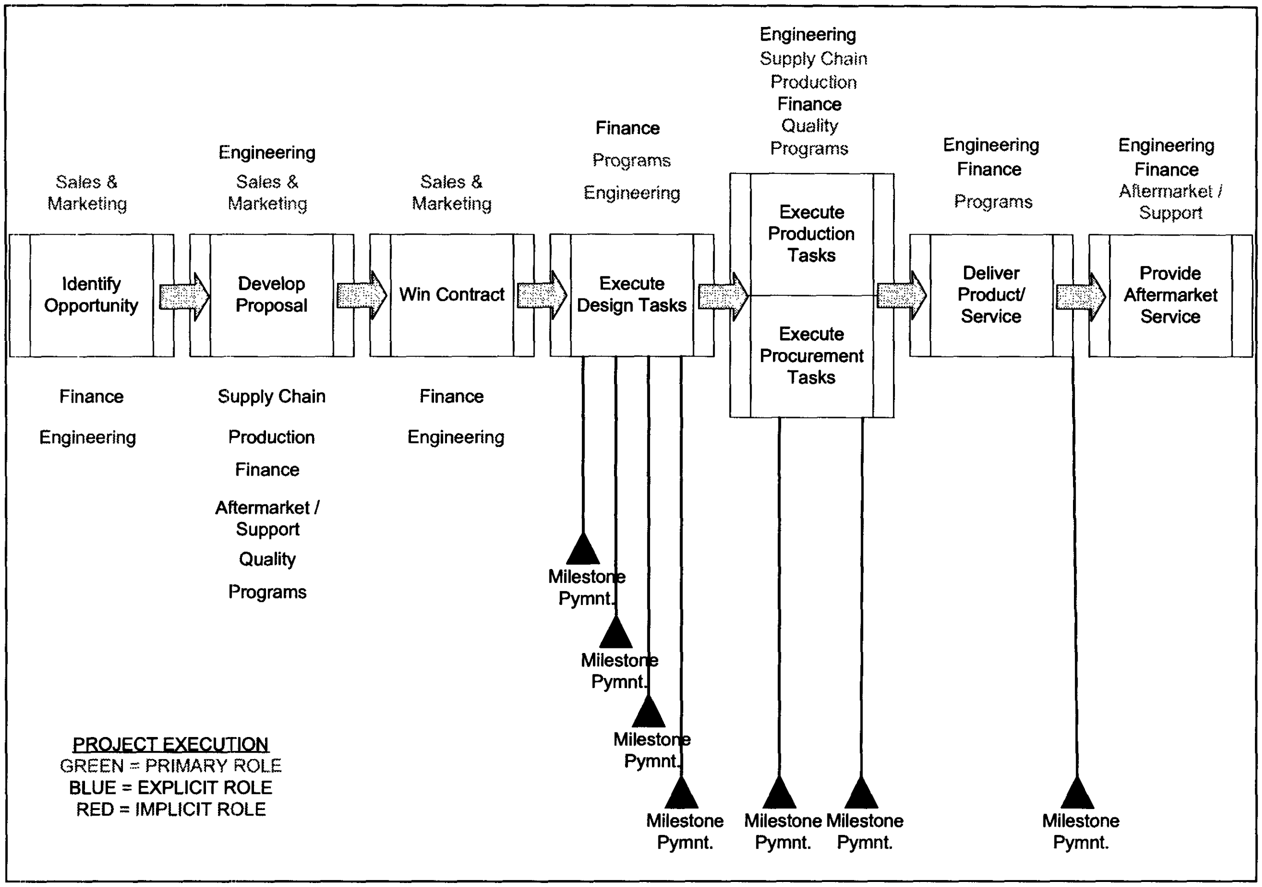


Figure 13. Project Execution, Primary, Explicit, and Implicit Roles

Project execution begins prior to contract award with identification of business opportunities. Once an opportunity has been identified, representatives from all groups within the organization are brought together to develop a proposal, typically in response to a request for proposal (RFP). Once a proposal has been forwarded to the potential customer, and a contract is won, the major design task execution is initiated and continues until drawings and procurement specifications are available for purchase and production of hardware. When hardware components are assembled into deliverable assemblies and validation testing is completed, they may be shipped for delivery to the customer. Once the equipment is installed, integrated with interfacing ship components, and commissioned for operation, periodic support continues through the life of the ship as components require refurbishment or replacement.

For each phase in the project execution one or more groups have a primary role. A primary role is defined as one with accountability and responsibility for management and execution of tasks in this phase of the project. A primary role player is "first in line" for manifestations of schedule and budget pressure as "applied" by senior/financial managers within the division. For example, during the Execute Design Tasks phase, the primary responsibility lies with the engineering and programs groups. Besides the primary role, there are secondary, explicit roles that are played by other groups within the organization. The secondary, explicit role is one that is supportive of the primary role players, providing data, information, monitoring, advice, etc. to support execution of the project tasks within any given phase. The support provided by the secondary explicit role players is both visible and expected. During a proposal effort, although the sales and marketing group may have primary role responsibility, support from every other group within the organization is needed for an effective response to the RFP. A third role is also secondary in nature, but is implicit. It differs from the explicit role in that it is no less crucial or critical, but is often "behind the scenes" or "below the radar" difficult to identify in formal workflow diagrams, production routings, or program management schedules/forecasts, and almost impossible to measure the impact or value of to the organization. It is immediately obvious, from inspection, that the engineering group holds this third role, exclusively through the project execution process. The product/service knowledge content which resides in the engineering group is often leveraged when questions arise, production errors are made, technical input is required, and generically, when decisions are made throughout the entire project execution process.

Using historic data and personal experience a directed graph was created to identify how the various secondary groups involved provide information, data, or generically "services" that are critical to execution of project tasks for the primary (accountable) groups. The directed graph was used to develop a design structure matrix, or in the vernacular of social network analysis, an adjacency matrix. Simple matrix multiplication techniques were applied to characterize the role of engineering in the project task execution process and the likely implications for frequency and type of interruptions that an engineering resource may encounter. A directed graph of the primary/secondary players in the organization is depicted in Figure 14 below.

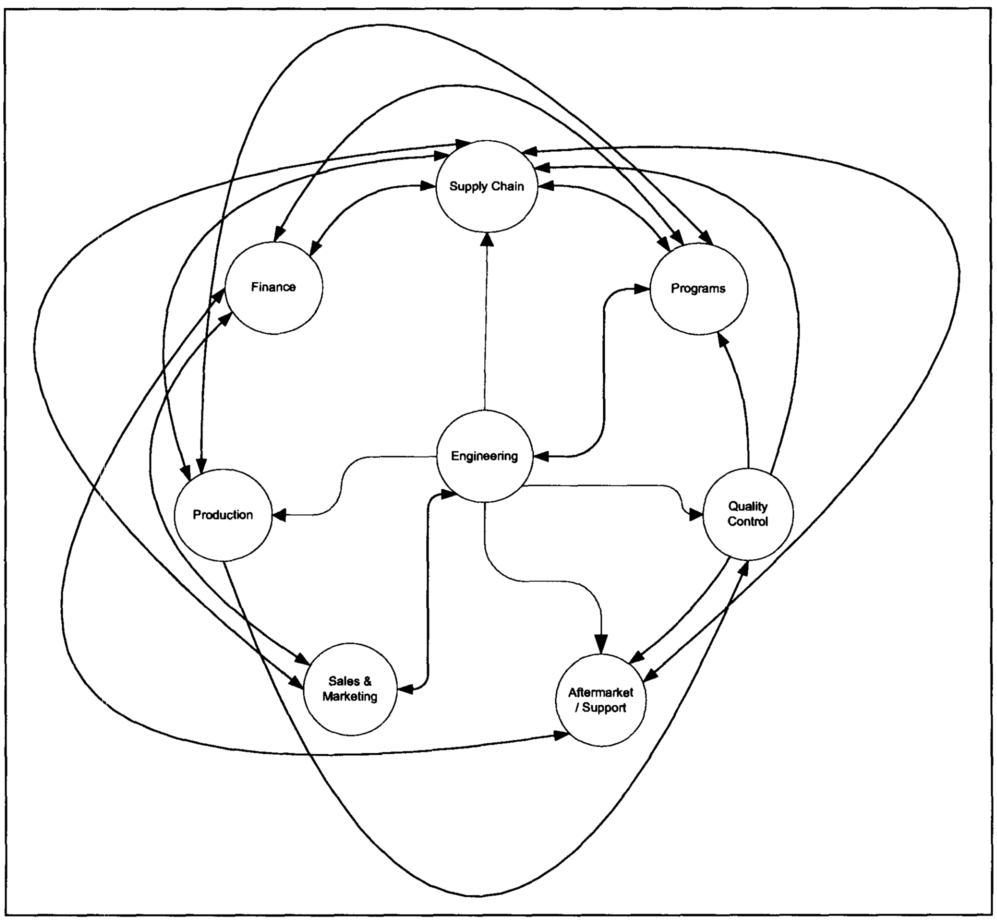


Figure 14. Directed Graph Primary/Secondary Roles - ("provides critical information to")

Figure 15 below is the adjacency matrix derived from the directed graph above.

Service Provided By		Service Received By							
		Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
	Finance/Accounting	0	1	1	1	1	1	1	0
	Programs	1	0	1	1	0	1	1	1
	Marketing/Sales	1	1	0	0	1	0	1	1
	Aftermarket/Service	1	0	1	0	0	0	1	0
	Quality Control	0	1	0	1	0	1	1	0
	Production	0	1	0	0	0	0	1	0
	Supply Chain	1	1	1	1	0	1	0	0
	Engineering	0	1	1	1	1	1	1	0

Figure 15. Critical Information Adjacency Matrix (Binary)

4.3 Causal Loop Diagramming

Observations collected during the interview process and results of the network analysis were used to develop a series of causal loop diagrams to describe the apparent (i.e. perceived), and potential causal relationships, and feedback mechanisms embedded in the structure of the project execution processes. Causal loop diagramming techniques are the first step in the development of formal system dynamics models. The diagrams are used to help identify those variables that play a primary and or influential role in generating observed behavior within the system of interest. Part of the causal loop diagramming process also involves generation of reference modes. The reference modes are based on perceptions and interpretation of selected and subjective data, observed by the participants in the system. These are qualitative (and sometimes quantitative) time series representations of a particular variable or metric of interest. They describe the behavior of variables in the past and up to the present. They may also serve as a predictor for future trends under status quo assumptions for policies embedded in the system, or potential changes in response to new/modified policies.

Several causal loop diagrams were developed throughout the interview process. Ultimately, only those that had extensions or pertinence to the project task execution process and the potential impact of interruptions were used in the formal modeling of the dynamic system of interest. For method illustration purposes, Figure 16 below depicts a causal loop diagram captured during one of the group interviews with the program management staff.

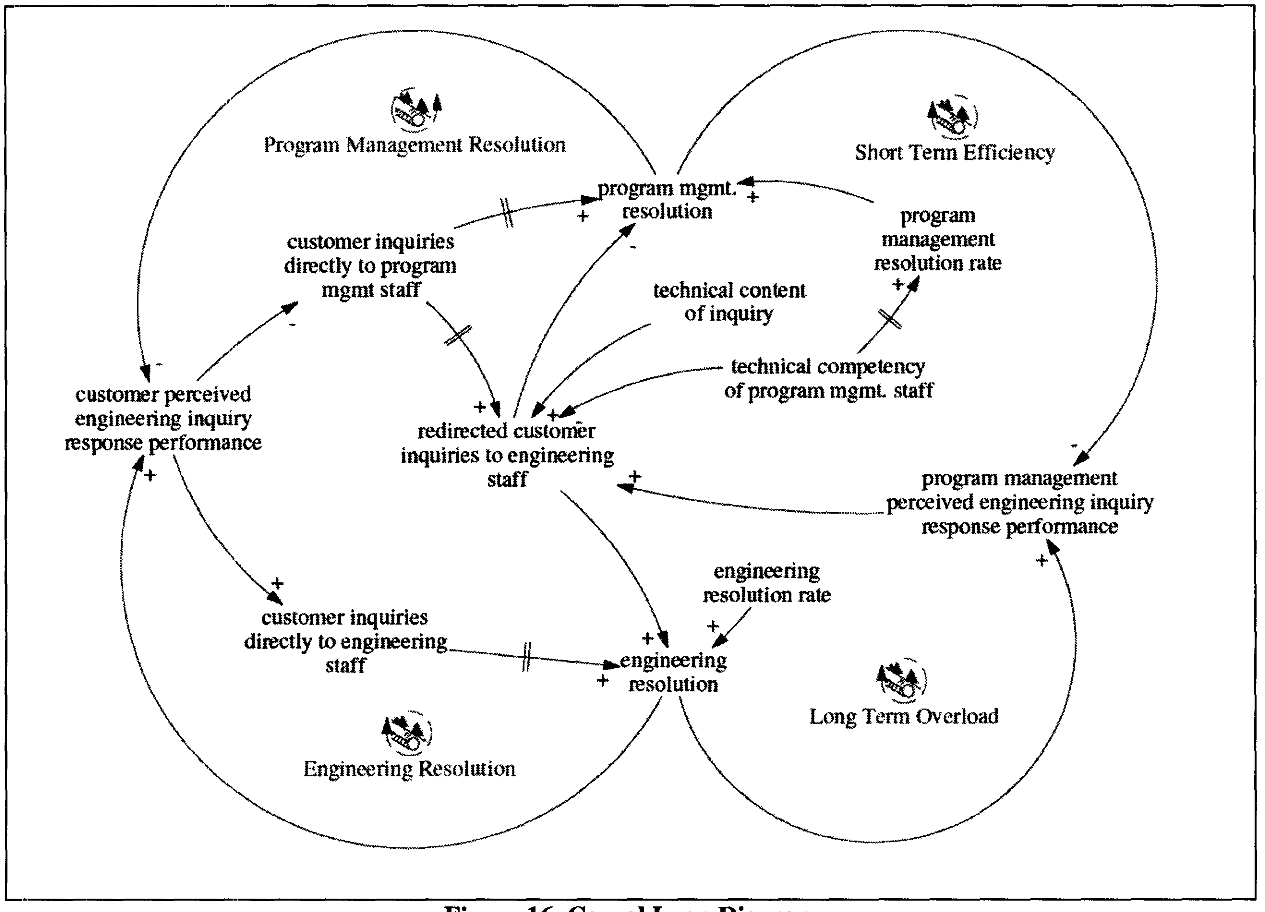


Figure 16. Causal Loop Diagram

The causal loop diagram in the figure above represents, pictorially, the cause and effect structure of a dynamic hypothesis. The dynamic hypothesis is a statement, or series of statements that propose to explain the behavior of a system in terms of cause and effect. In this case the dynamic hypothesis can be described as follows:

Dynamic Hypothesis: Best intentions undermine project management & engineering task execution

- Customer inquiries come in to either the program office or engineering
- The customer always tries to get answers from what they perceive to be the most efficient source of value
- Because of technical content, some portion of the inquiries to program office are routed to engineering
- The following factors lead the customer to contact engineering directly:
    - Technical knowledge
    - Historical working relationship
    - Ease of Contact/Response time
- The customer's perception of engineering as the most efficient source of value is reinforced such that the next time they will be more likely to call engineering directly
- This results in:
    - More interruptions for engineering
    - Less transfer of project technical knowledge to program managers
    - Erosion of customer confidence in program office as source of value

Four explicit feedback "loops" have been identified in the causal loop diagram. One loop, "Engineering Resolution", describes how the resolution of inquiries by the engineering department effects the customer's perception of the efficiency (i.e. speed + quality = value) of the engineering department relative to that of the programs department. The second loop, "Program Management Resolution", describes the impact of program management resolution of inquiries on this same perception of efficiency. The perceived efficiency is ostensibly a relative measure between engineering and programs inquiry resolutions. The third loop, "Short Term Efficiency", seeks to describe the effect of the relative efficiency of the engineering and programs on the tendency of program management to redirect their inquiries to the engineering department. The fourth loop, "Long Term Overload", again describes the effect of the relative efficiency of the engineering department on the tendency of program management to redirect their inquiries to the engineering department; this time from the perspective of the engineers.

The causal arrows (links) that are drawn between variables provide an indication of how the variables behave with respect to each other. For example, if a causal link drawn from "variable 1" to "variable 2" and the sign of the arrow is "+", this can be translated as: "when variable 1 increases, variable 2 increases (or when variable 1 decreases, variable 2 decreases)". The "+" indicates that the two variables move in the same direction. If, on the other hand, the causal link is labeled with "-", this can be translated as: "when variable 1 increases, variable 2 decreases (or when variable 1 decreases, variable 2 increases)". The "-" indicates that the two variables move in the opposite direction. When a series of variables are connected such that the path recourses back to a previous variable a "loop" is created. Any given loop can be characterized as reinforcing, or balancing. A reinforcing loop is one in which an increase in any variable in the loop results in a further increase in the same variable as the loop is "traversed". A balancing loop is one in which an increase in any variable in the loop results in a decrease in the same variable as the loop is "traversed".

Each of the four loops is a reinforcing feedback loop. That is, the tendency of cause and effect is to be amplified and reinforced over time, all else the same. With two or more reinforcing loops in the system there is a variety of behaviors that is possible, depending on the relative "strength" of the loops at any given time. Embedded delays within the system (depicted as arrows with a pair of crossing line segments), may also play a significant role in the behavior of the system. With a little imagination, and no further modeling, it may be implied from the structure depicted from the causal loop diagram above, that, given an assumed technical competency advantage of the engineering department over the programs department, and an implied motivation for program management to respond quickly to customer inquiries and customers to seek out better/faster answers, that more and more questions are directed , and redirected to engineering, fewer and fewer are directed to or handled by programs over time resulting in greater scope of accountability for engineering, and less time to complete project work. The power of causal loop diagramming lies in identification of possible behaviors given the structure, and may point to additional variables, loops, etc. that could further expand or further limit the number of possible behaviors that the system structure could result in.

4.3 System Dynamics Modeling

Causal loop diagramming provides a necessary first step in understanding the potential dynamics that a system structure may enact. However, the effect of shifts in feedback loop strength over time, and delays within the system can have a significant impact on the specific behavior that is exhibited. These impacts cannot be quantified through causal loop diagramming alone. System dynamics modeling, as an adjunct, provides the mechanisms to assess these impacts and provide insights of when, why, and how feedback loop strengths may change, and/or what the impacts of delays (and/or resulting accumulations) of various types and durations will have on the system behavior. With appropriate choice of variable values, and validation against historic system measurements, it is possible to replicate not only system behavior trends, but also quantitative variations over time for each variable in the system. The mechanisms through which system dynamics is able to replicate these impacts are known as "stocks" and "flows". Stocks are accumulations, (integrations, mathematically speaking). As such, they are also a type of delay; they provide a "warehouse" that can hold stuff (e.g. dollars, inquiries, chickens, etc.) for some dwell time. Flows are the rate of change of a stock (derivatives, mathematically speaking). Flows are used to build-up and drain-down stocks. Figure 17 below depicts the representation for a stock/flow structure.

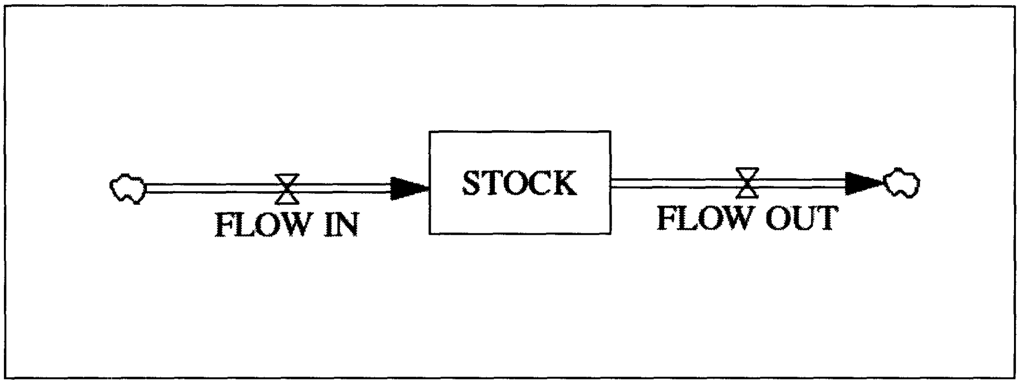


Figure 17. Generic Stock-Flow Structure

Once a CLD has been formulated, stocks and flows can be added to the diagram, and some of the variables converted to more "operational" parameters, resulting in a formal system dynamics model. This can involve reformulation of variables into quantifiable units, and/or addition of auxiliary parameters, look up tables, etc. to facilitate computational exercise of the model. Figure 18, below depicts a formal, if somewhat simplified, system dynamics model based on the CLD example from the previous section. Only two of the reinforcing loops are modeled here for the sake of brevity and clarity.

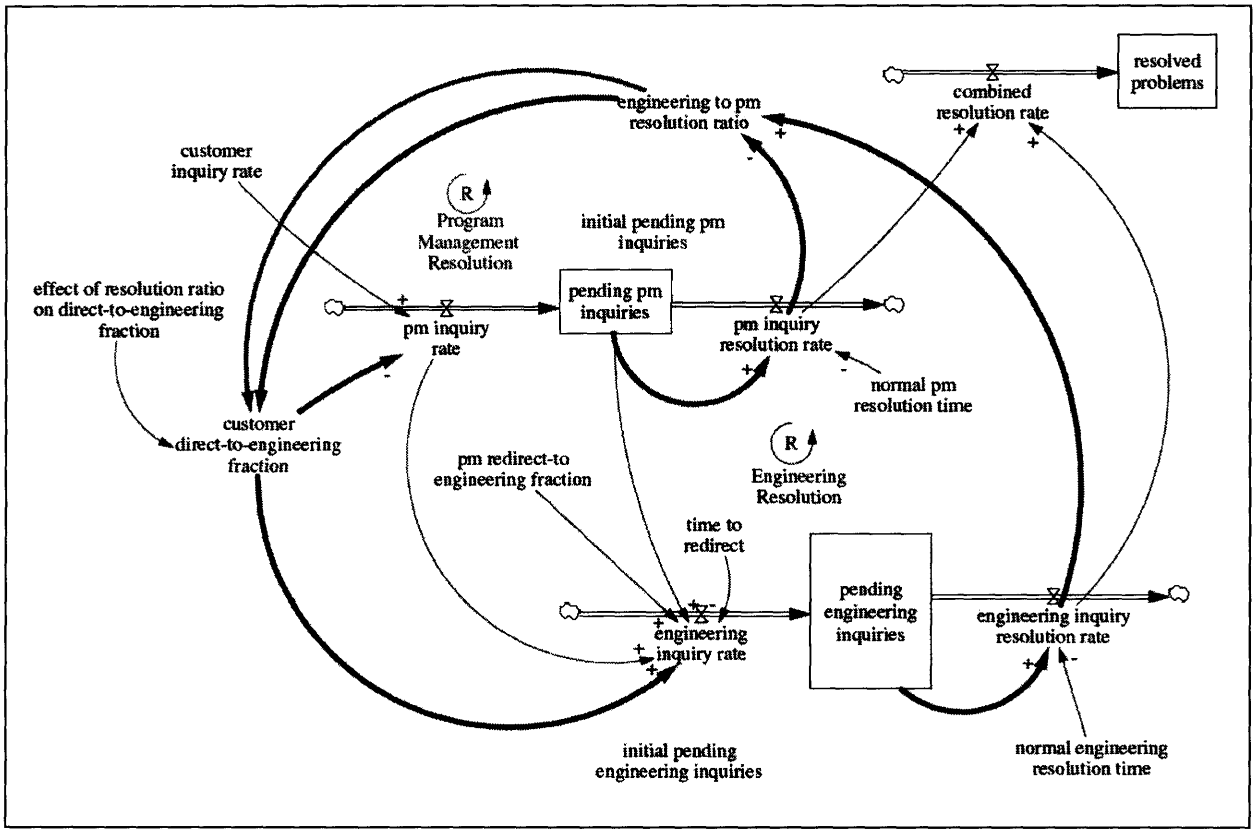


Figure 18. System Dynamics Model of Customer Inquiry Routing Dynamics (Example)

In this model there are three stocks: "*pending pm inquiries*", "*pending engineering inquiries*", and "*resolved problems*". The first two stocks keep track of the accumulation of inquiries to program management and engineering as an integral formulation of the difference between rate of inquiry generation and rate of inquiry resolution. In other words,

$$pending\ inquiries = initial\ pending\ inquiries + \int (inquiry\ rate - resolution\ rate)\, dt$$

The rate at which inquiries come into engineering (or program management) is based on the customer inquiry rate and the fraction of those inquiries that are directed to engineering versus program management. In addition, there is also a dependency based on the fraction of inquiries that come into program management which are re-directed to engineering due to technical content (or the whim/discretion of the program manager).

The rate at which inquiries are resolved by engineering (or program management) is based on the number of pending inquiries and a normal(or typical) time to resolve an inquiry by each of the two groups. The combined (i.e. summed) resolution rate of the two groups is what is seen by the customer as an aggregate, which feeds into a stock of resolved problems. In this case the stock only grows in size because there is no mechanism (i.e. output rate) implemented to "drain" this stock and the combined resolution rate can never be negative.

The principal feedback in the system is the effect of the engineering and program management resolution rates on the customer's perception of which group is most effective at returning correct answers quickly. The implicit assumption in this model is that the inquiry resolution rates of both the engineering group and the program management group are visible to the customer, such that the "*engineering to pm resolution ratio*" can be formulated and measured over time. Under the conditions of this assumption, customer behavior policy is modeled through use of a piecewise continuous look-up function, "*effect of resolution ratio on customer direct-to-engineering fraction*". A plot of this look-up function is shown below in Figure 19.

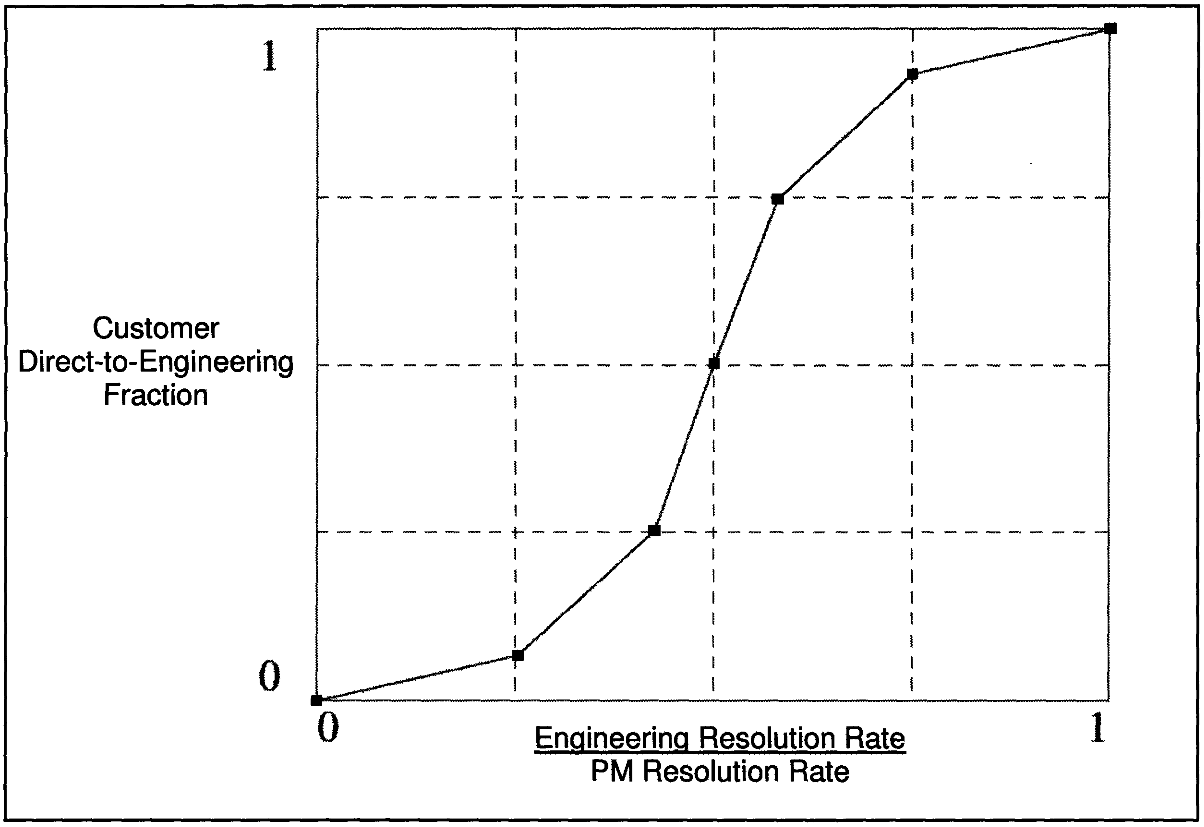


Figure 19. Effect of Resolution Ratio on Customer Direct-to-Engineering Fraction

As the ratio of engineering resolution rate to program management resolution rate increases, the fraction of inquiries that the customer directs to engineering increases monotonically. This continues until the point at which the ratio becomes 1 or greater, at which point, all inquiries are directed to the engineering department and none to the program management department.

Simulation of the model confirms this behavior. Even with the normal resolution rate of the program management department set at 1/3 of the rate of the engineering department, and under the assumption that only 25% of the inquiries into the program management department are redirected to engineering, it still takes but a single month before the customer is directing all inquiries to the engineering department. Output from the simulation, coded in Vensim© is depicted in Figures 20, 21, 22 below.

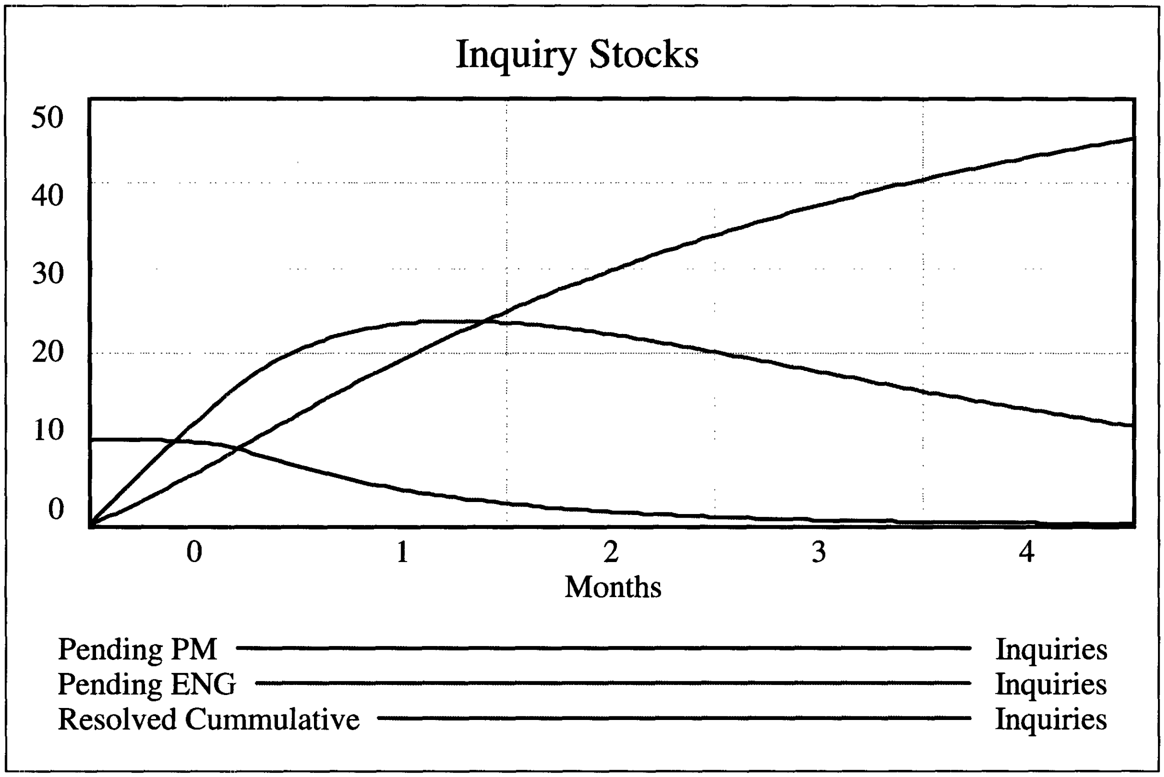


Figure 20. Pending and Resolved Customer Inquiries

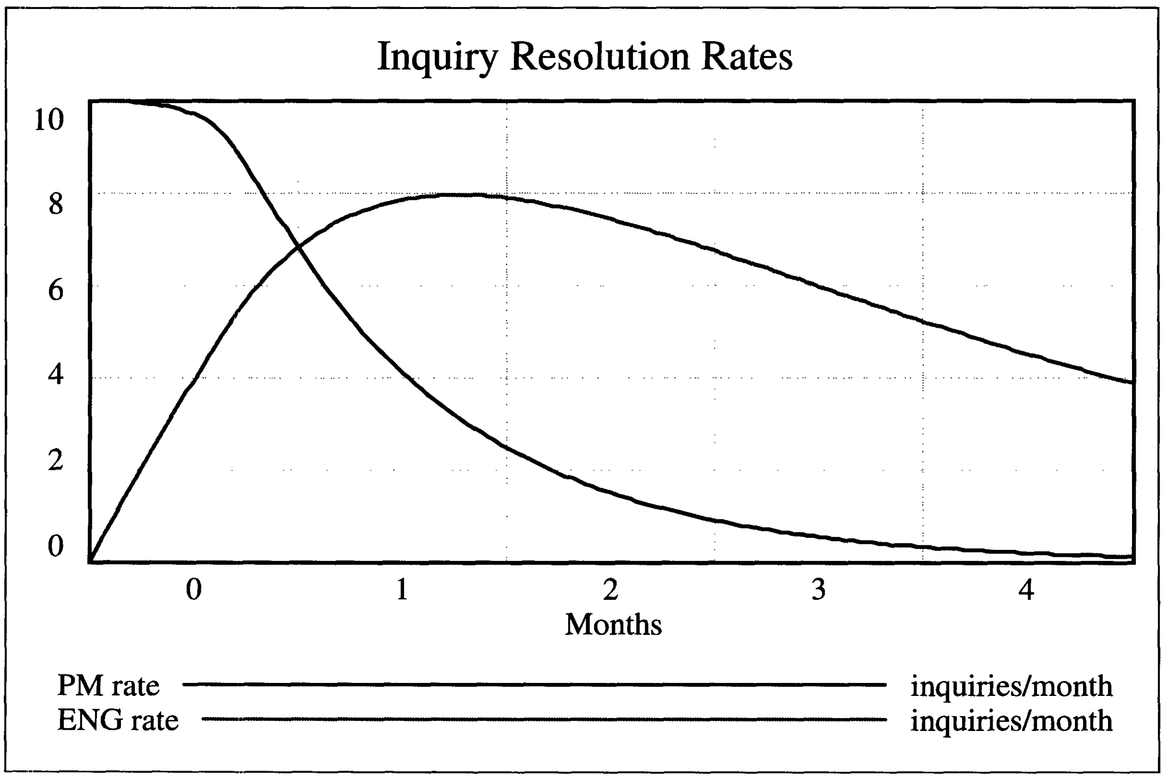


Figure 21. Inquiry Resolution Rates

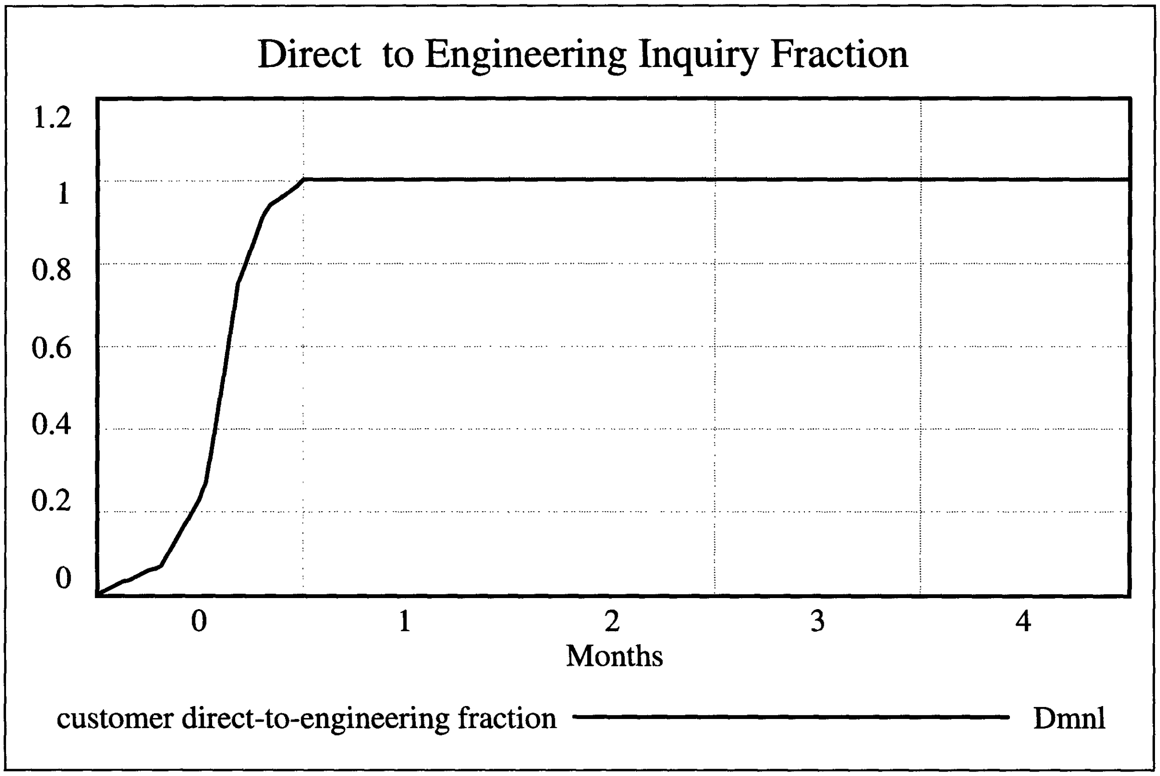


Figure 22. Customer Direct-to-Engineering Inquiry Fraction

This sample model is intended to provide a simple example of the system dynamics tools and methods used to model the dynamics of interruptions in engineering project task execution.

The following section will describe the results of interviews, network analyses, causal loop diagramming, and formal system dynamics modeling undertaken for the current research of the dynamic impacts of interruptions to engineering project task execution.

5.0 RESULTS

This chapter provides the results of the various analyses and techniques used as part of the research effort. A discussion of these results and their implication will be provided in the next major section of this thesis. The current section will summarize the results of (1)the interviews, (2) the network analyses, (3) the causal loop diagramming, (4) the system dynamics modeling, and (5) the dynamic simulation output of the formal model.

5.1 Interview Results

A series of informal/unstructured interviews were conducted in groups and with selected individuals throughout the organization. The group interviews were conducted as "round-table" discussions wherein I served as the moderator. Comments, opinions, and perceptions were captured using a whiteboard during the group discussion. For the one-on-one interviews, I took hand written notes. Despite starting the initial discussions with the questions of what is the problem with engineering and/or what is the problem with engineering's role in the organization, the comments and observations were quite varied and covered a wide range of issues. Recurring themes and issues which generated a great deal of reaction (analytical or emotional) were identified as potential areas of focus for the follow-up interviews, the network analyses and causal loop diagramming. An attempt was made to group the comments and observations into five major categories:

- **Resources**
- **Priorities**
- **Cost/Schedule Performance**
- **Processes/Capabilities**
- **Leadership**

The grouping of comments into these broad categories was somewhat subjective. At times it could even be considered artificial due to blurred boundaries between the categories, and the multiple category implications of some of the comments. But nevertheless, categorization provided a means to identify major themes, from which, could be selected a focus for causal loop diagramming and system dynamics modeling. Figures 23, 24, 25, 26, 27 below provide a listing, by category, of the comments reflecting the major or recurring themes captured during the interviewing process.

On Engineering Resources....

- "it doesn't make sense that there are more people managing the projects than engineers working on them
- "we are stretched so thin that we have short changed R&D and any process improvement efforts over the last 4 years"
- "it is very difficult to justify more engineering resources"
- "there's not enough engineers to support the IPT/Project team paradigm"
- "they're behind on everything, just hire some more damned engineers"
- "we [aftermarket/service]don't see a problem with getting answers out of engineering"
- "you guys think you're supermen, you never ask for help until it's too late"
- "you need more creativity in addressing the resource issues"
- "[resources,] it's always 99% of the discussion, but it's reality and it's not going away"
- "a snake can only swallow a pig so large"
- "it seems like you guys are afraid to give up your work to anyone else"
- "the weekly interface meetings with [resource coordinator] are focused on providing the ammo he needs to back up requests for more resources"

Figure 23. Comments About Engineering Resources

On Setting Priorities….

- "engineering is expected to resolve project schedule conflicts"
- "there is no realization within the greater organization to what degree that engineering is faced with conflicting priorities"
- "we are constantly given new or multiple #1 priorities"
- "engineering priority setting process is insufficient, and communication of priorities is lacking too"
- "just decide what your priorities are and then just tell the program managers what they are"
- "everything has top priority"
- "every project task becomes a fire drill, eventually"
- "you guys [engineering]always drop what you're doing to help us [aftermarket/service]out"
- "priority setting between projects is a program management responsibility – if there are other conflicts within the organization, that's what staff meetings are for"

Figure 24. Comments About Priorities

On Cost/Schedule Performance….

- "we [engineering dept] don't make budgets, we are told what they will be"
- "there is no internal mechanism to address scope changes "
- "incomplete, inaccurate, or preliminary information results in a lot of rework"
- "engineering is held accountable for schedule/cost overruns due to schedule compression that we have no control over"
- "we're [engineering] the light at the head of the train; since we have to get our stuff done first, everyone else is always trying to make up for our delays"
- "we [engineering] do too much "free" work that's not accounted for"
- "you [engineering] guys have too many overruns and not enough scrutiny"
- "you [engineering]never seem to know what it will really take to complete tasks"
- "the engineering department has become the [other formerly really bad department] of old – it'll be done when it's done, and it'll cost what it costs"
- "we [programs]don't even know what's coming until it's too late"

Figure 25. Comments About Cost/Schedule Performance

On Engineering Processes/Capabilities….

- "there is too much unplanable work, [engineering resource coordinator] has been helping us understand how much"
- "we [engineering] have to write the sales proposals; no one else knows enough about the products"
- "we used to have application engineers who had the technical skills to do proposals, manage technical programs, etc. The new program mangers are more like an extension of finance"
- "the greater organization is technically very weak"
- "[experienced engineer] is the de-facto project engineer for every project"
- "there is no way to assess the knock-on effects of changes in priority"
- "it would be good to have a capability/responsibility matrix"
- "you [engineering] guys need more flexibility, and you need to delegate more decision authority"
- "you [engineering] not doing enough value engineering – I.e. improving existing products, internal research and development, product development, capability enhancement"
- "there's no [engineering] bench strength"
- "still too much small company mentality – silo survival, and difficulty in capture of best practice"
- "you [engineering] need to provide information/training to empower others to make decisions"

Figure 26. Comments About Processes/Capabilities

On Engineering Leadership….

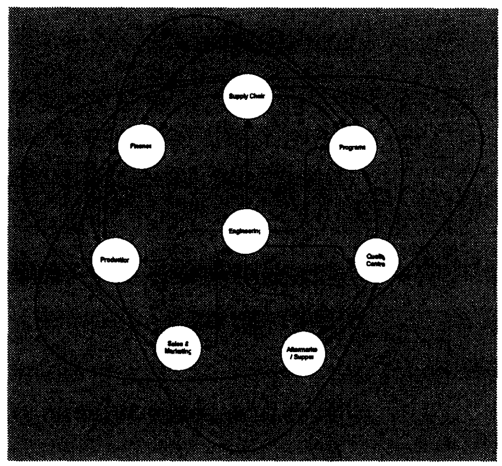
- "having a distant manager creates communication difficulties – timeliness of responses, flow down of information, and explanation times"
- "the [manager at a]distance thing doesn't look like a problem from my perspective – there must be a process at work"
- "the teaching [process] is not apparent. (Engineering) needs to arm the front end of the business?"
- "process and behavior is not being driven – it's a leadership issue"
- "[experienced engineer] is overburdened with decision making responsibility"
- "don't tell me you're too busy to do your job, you need to have discipline [about developing resource capability]"
- "[engineering resource coordinator] is good at interfacing with the other groups"
- "It's not clear who is in charge of engineering resource allocation
- "I don't think the project leaders have a good understanding of the engineering capabilities around the organization – you guys aren't selling them very well."

Figure 27. Comments About Leadership

5.2 Network Analysis Results

A simple network analysis was conducted to quantitatively and qualitatively assess the linkages that exist within the organization. Of particular focus are the relationships that exist between the engineering resources and the rest of the organization in the context of project task execution. An adjacency matrix was developed (as previously described in the methods section of this document) utilizing a directed graph. Figure 28 below depicts the adjacency matrix as well as the "square" and "cube" of the adjacency matrix as well.

Service Provided By \ Service Received By	Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
Finance/Accounting	0	1	1	1	1	1	1	0
Programs	1	0	1	1	0	1	1	1
Marketing/Sales	1	1	0	0	1	0	1	1
Aftermarket/Service	1	0	1	0	0	0	1	0
Quality Control	0	1	0	1	0	1	1	0
Production	0	1	0	0	0	0	1	0
Supply Chain	1	1	1	1	0	1	0	0
Engineering	0	1	1	1	1	1	1	0



Service Provided By \ Service Received By	Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
Finance/Accounting	4	4	3	3	1	3	5	2
Programs	3	5	4	3	3	3	5	1
Marketing/Sales	2	4	4	5	2	5	4	1
Aftermarket/Service	2	3	2	2	2	2	2	1
Quality Control	3	2	3	2	0	2	3	1
Production	2	1	2	2	0	2	1	1
Supply Chain	3	3	3	2	2	2	5	2
Engineering	4	4	3	3	1	3	5	2

Service Provided By \ Service Received By	Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
Finance/Accounting	15	18	18	16	9	16	20	7
Programs	17	19	17	17	8	17	22	9
Marketing/Sales	17	18	16	13	7	13	23	8
Aftermarket/Service	9	11	10	10	5	10	14	5
Quality Control	10	12	11	9	7	9	13	5
Production	6	8	7	5	5	5	10	3
Supply Chain	13	17	15	15	8	15	17	6
Engineering	15	18	18	16	9	16	20	7

Figure 28. Adjacency Matrix Recursive Self-Multiplication

The following can be summarized from the analysis of the adjacency matrix raised to the first, second, and third powers:

- Engineering receives critical information for completing project tasks for which they are accountable from only two other groups – programs and marketing/sales – the fewest of any group.
- Engineering provides critical information to six other groups (all except finance) to aid them in fulfilling project tasks for which they are accountable – the most of any group except for finance.
- Engineering is connected to itself by pathways of length two, two times – i.e. engineering has reciprocal ties with 2 other groups. Only production (reciprocity with 2 other groups), and quality control (reciprocity with no other group) have less than or equal number of reciprocal ties.
- Engineering is connected to itself by pathways of length three, seven times – the same as quality control. Only production has fewer (5).

Figure 29 below depicts the transpose of the adjacency matrix and the correlation between the adjacency matrix and its transpose. For each cell in the correlation matrix, a "1" is used when the corresponding cells of the adjacency matrix and its transpose are the same, and a "0" is used when the corresponding cells of the adjacency matrix and its transpose are different. This results in a symmetric matrix, describing the degree of "reciprocity" between the groups.

Adjacency Matrix Transpose	Service Received By							
Service Provided By	Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
Finance/Accounting	[illegible]	1	1	1	0	0	1	0
Programs	1	0	1	0	1	1	1	1
Marketing/Sales	1	1	0	1	0	0	1	1
Aftermarket/Service	1	1	0	0	1	0	1	1
Quality Control	1	0	1	0	0	0	0	1
Production	1	1	0	0	1	0	1	1
Supply Chain	1	1	1	1	1	1	0	1
Engineering	0	1	1	0	0	0	0	0

Correlation of Adjacency Matrix and Transpose	Service Received By							
Service Provided By	Finance/Accounting	Programs	Marketing/Sales	Aftermarket/Service	Quality Control	Production	Supply Chain / SRS	Engineering
Finance/Accounting	1	1	1	1	0	0	1	1
Programs	1	1	1	0	0	1	1	1
Marketing/Sales	1	1	1	0	0	1	1	1
Aftermarket/Service	1	0	0	1	0	1	1	0
Quality Control	0	0	0	0	1	0	0	0
Production	0	1	1	1	0	1	1	0
Supply Chain	1	1	1	1	0	1	1	0
Engineering	1	1	1	0	0	0	0	1

Figure 29. Transpose of Adjacency Matrix and Correlation

The following can be summarized for the analysis of the correlation between the adjacency and matrix and its transpose:

- A reciprocal relationship exists between engineering and finance where no critical information is exchanged directly
- A reciprocal relationship exists between engineering and programs where critical information is exchanged directly
- A reciprocal relationship exists between engineering and sales/marketing where critical information is exchanged directly

5.3 Causal Loop Diagramming Results

Observations collected during the interview process and results of the network analysis were used to develop a series of causal loop diagrams to describe the apparent (i.e. perceived), and potential causal relationships, and feedback mechanisms embedded in the structure of the project execution processes. Reference modes were developed for the behavior over time of key goals of the engineering project task execution process, "On time", "Under Budget", and "Right the first Time". Figures 30, 31, & 32 below show the reference modes for these goals. The plots capture what the trend has been in the past and where the stakeholders would like to go in the future – assuming the right combination of structures, feedback path, and policies can be implemented. These plots were derived based primarily on comments provided by the engineering group staff, supervisor and manager, but are representative of and consistent with the viewpoints of other groups within the organization.

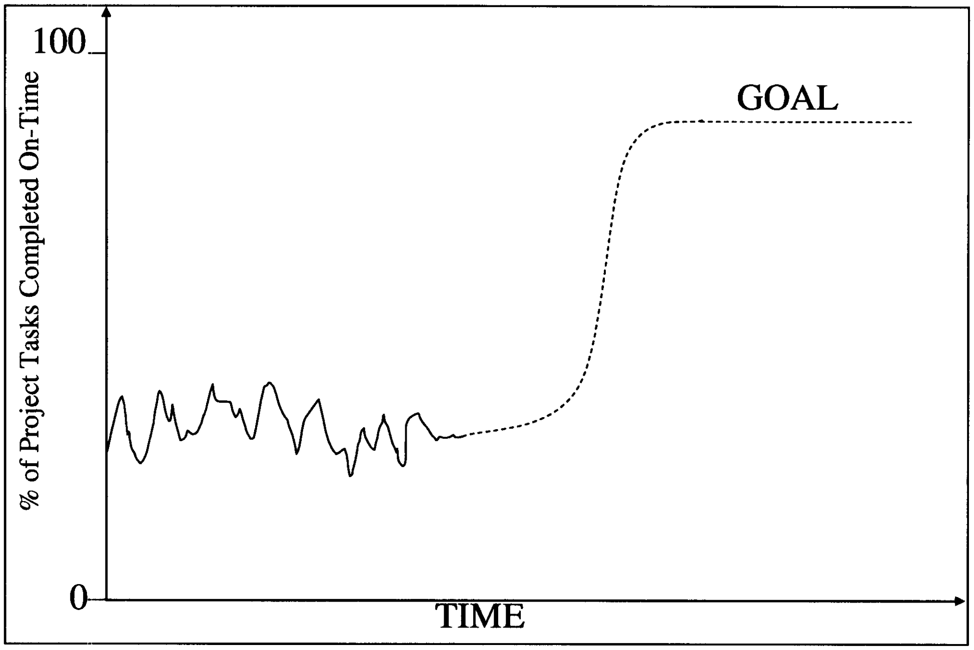


Figure 30. On Time Reference Mode

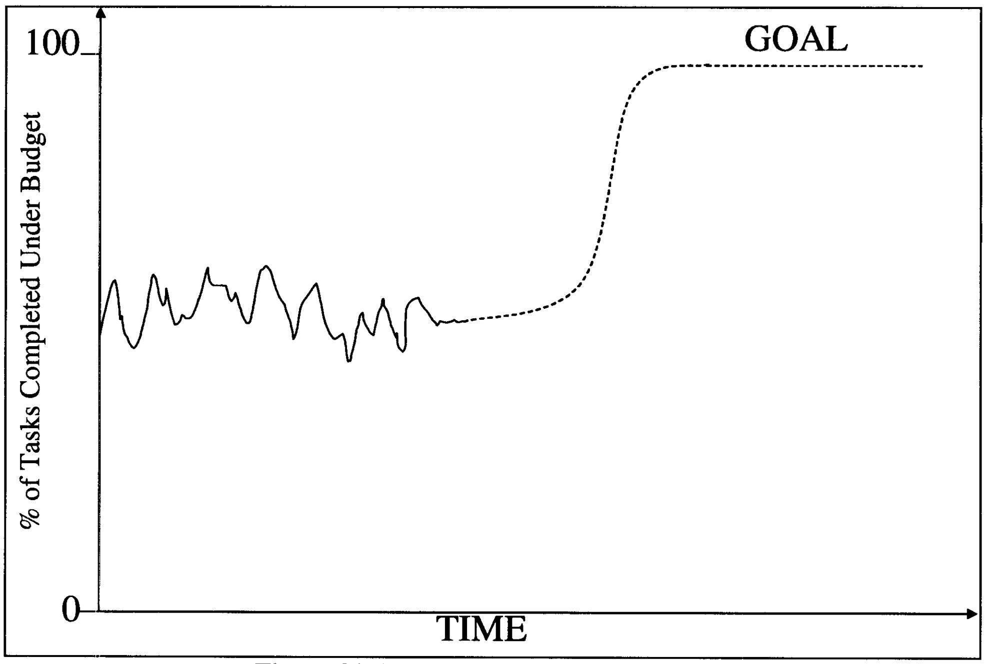


Figure 31. Under Budget Reference Mode

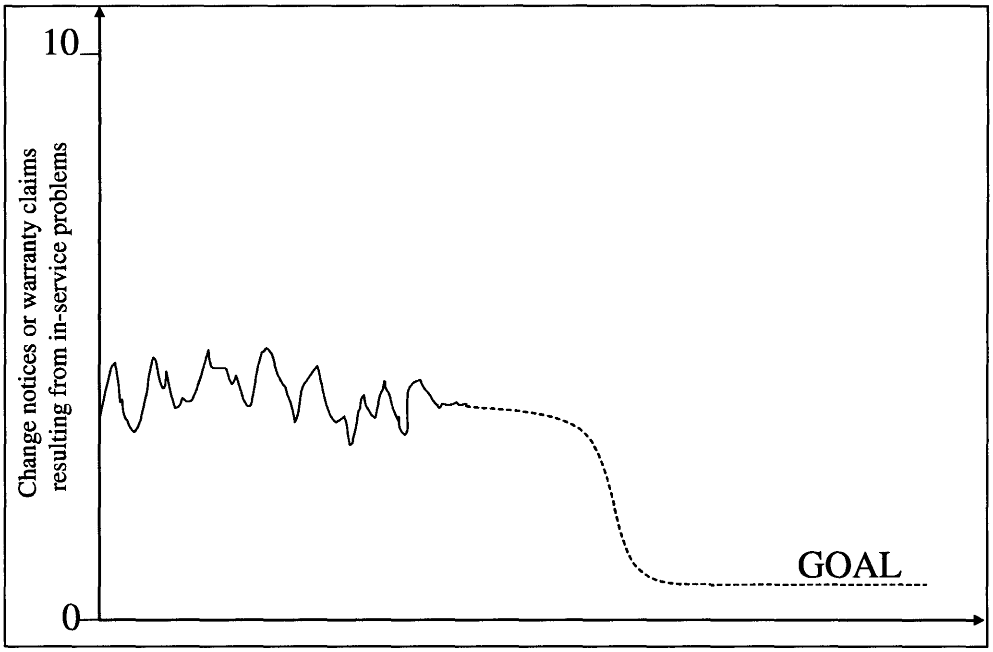


Figure 32. Right the First Time Reference Mode

A fourth reference mode was developed that attempted to capture the trend in performance and capability of the engineering group, in the aggregate, over the long term. This reference mode is presented below in Figure 33. The slowly declining trend can be interpreted to represent the composite "perception" of all stakeholders that interface with the engineering group, including the self assessments by the engineering staff.

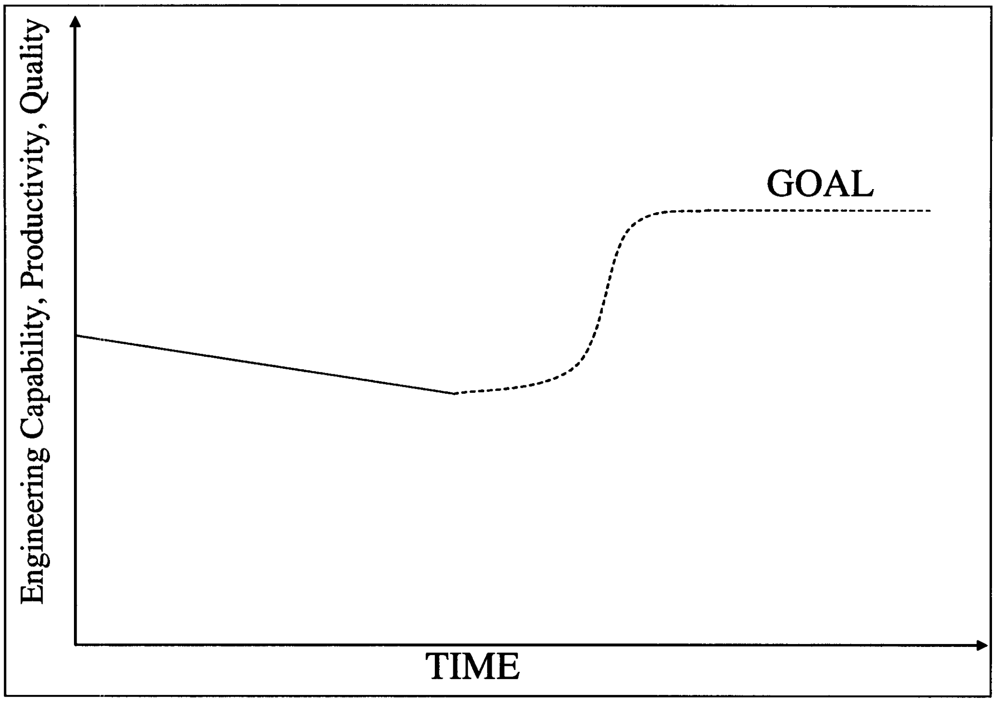


Figure 33. Engineering Capability/Performance Reference Mode

The results of the interviews and network analyses, as well as the reference modes depicted above led to several key observations that were selected to guide the causal loop diagramming process:

1. **Interruptions Impact Business Financial Metrics**: Interruptions during the normal work day for the engineering group have a significant perceived impact on project task completion

2. **Interruptions are Built Into the System**: Interruptions have a variety of immediacy and duration associated with them, but tend to be associated with services provided by the engineering group that are critical to completion of project tasks that other groups are accountable for.

3. **Engineers are the Keepers of Knowledge**: Technical knowledge of complex products/services is concentrated in engineering and service groups, and to a much lesser

degree in other groups. Transfer of knowledge is hampered by schedule pressure, and compromised by short term decision making practices.

4. **The Hegemony of the (Experienced) Engineer**: There is a perception that experienced and knowledgeable engineers do not exhibit the behaviors and process commitment to developing inexperienced staff, and educating the rest of the organization to a sufficient level. In extreme cases this leads to the perception that experienced engineers are "power hoarding", "self involved", or worried about job security.

5. **Always Late, Always Over Budget**: Delays in project task completion have a negative impact on schedule, budget, and the overall perception of engineering capability/performance by other groups. This leads to a desire for alternative resource allocation policy.

6. **Stable Permanent Workforce**: Although engineering resources are heavily utilized and stretched very thin, it is difficult to justify hiring of permanent engineering staff due to fluctuations in market demand for products and services, and competitive marketplace pressures.

7. **Helplessness**: There is a feeling of helplessness among the engineers in their inability to break out of the pattern of delays, and budget overruns. The perception amongst the engineers is that despite their best intentions, and exercise of good discipline and processes, that the system in which they operate has "stacked the odds" against them. From the perception of the other groups, this inability to change the pattern is perceived as an unwillingness to change old ways, and failure of engineering resource leadership.

For each one of the observations above, causal loop diagrams were developed to understand the underlying structure of the system.

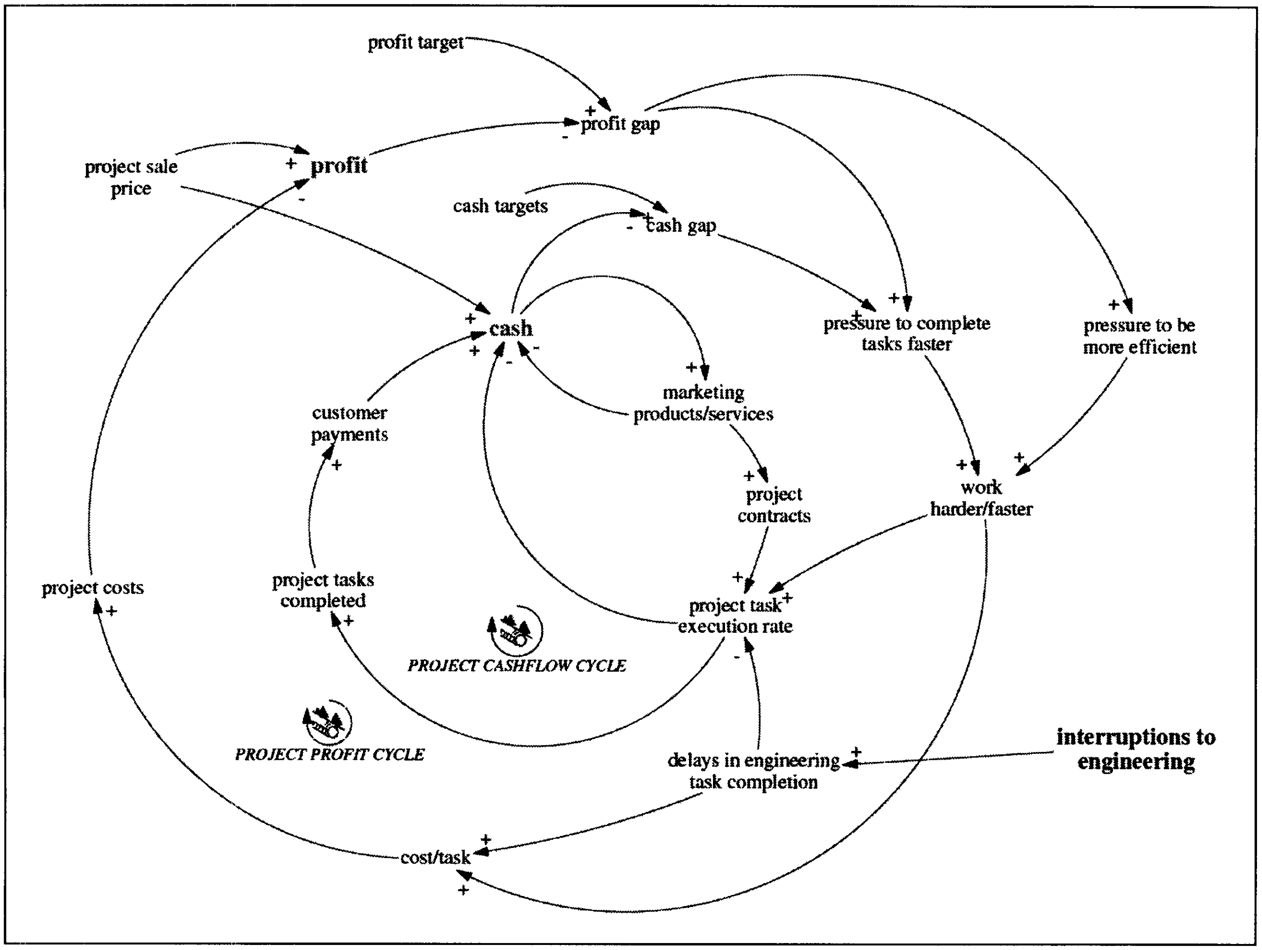


Figure 34. Interruptions Impact Business Financial Metrics CLD

The CLD in Figure 34 above describes how cash and profit are affected by interruptions in engineering project task execution. From the perspective of management the primary focus is the project cash flow cycle loop. This loop describes the fundamental business process wherein cash is used to market, sell and produce goods and/or services which, upon delivery to the customer is exchanged for cash, which allows the business cycle to continue. In addition to the cash flow cycle loop, management is also very concerned with the project profit cycle loop. This loop describes how the costs of marketing, selling, and producing the goods and/or services is related to the agreed upon cash value exchange for delivery. If it is assumed that a fixed price contract is in place, then the profit is driven by the costs of project execution. The primary feedback mechanisms are those associated with traditional financial metric monitoring. Although they may take many forms, the simplest formulation is a comparison of forecast (or budget) to actual expenditures and how they project to impact on profit and cash. In the business division that was studied, negative variances to forecasts will result in both schedule and cost pressure applied to the engineering department by the CFO directly, or through the program management group. In many cases the schedule pressure is the result of quarterly cash flow targets not being met. Typically the engineers are encouraged to work harder and faster as a result. Since they are salaried employees, this translates into more and more unpaid overtime. Interruptions cause the project work to be delayed through reducing the project task execution rate. In addition, delays also have a similar impact to broken set-ups in a manufacturing environment. In other words, they result in a decrement to productivity and a resulting increase in average cost per task as engineers are losing time trying to figure out where they left off on task execution before they were interrupted.

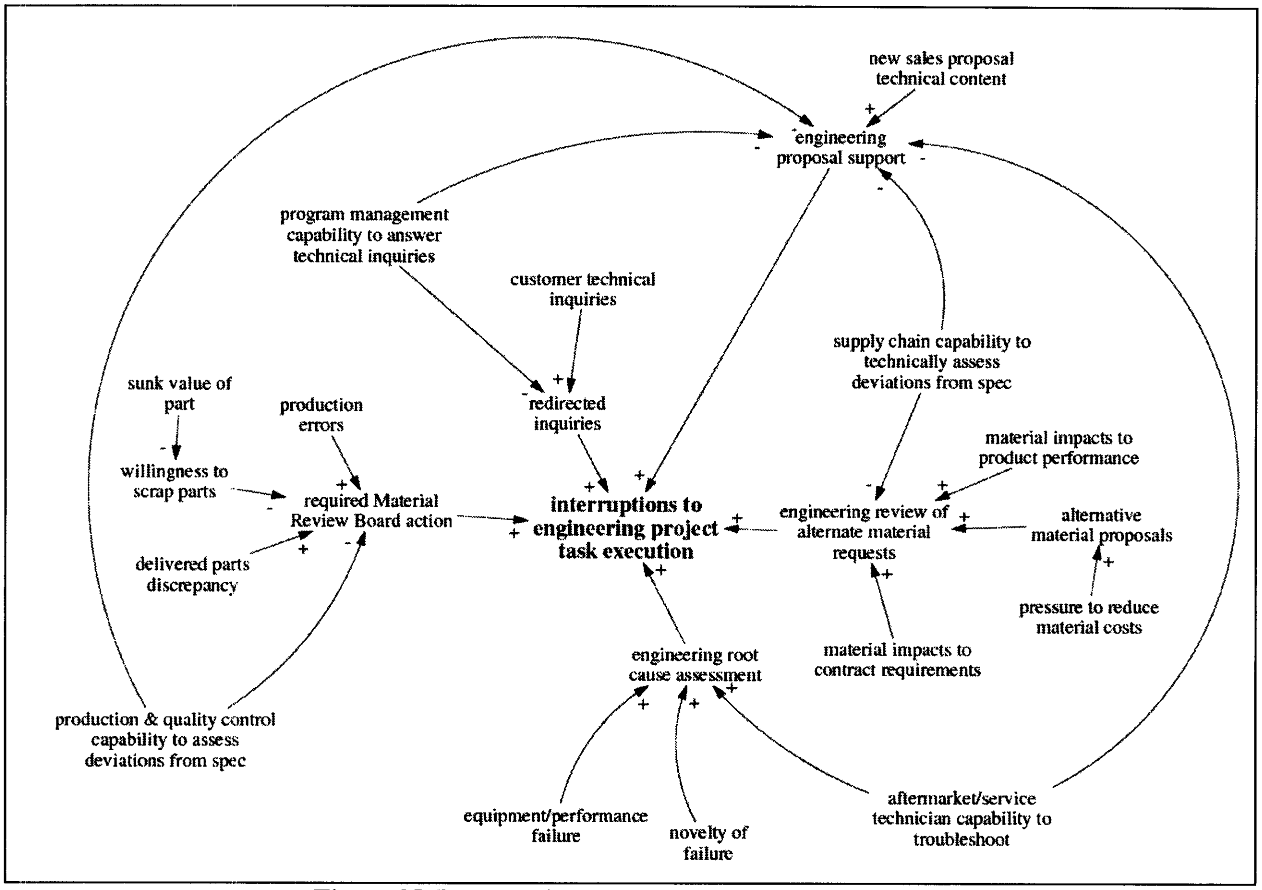


Figure 35. Interruptions are Built Into the System CLD

The CLD in Figure 35 above describes how interruptions are a fundamental part of the system. When customer inquiries come in to program management, if they are of sufficient technical content, the program managers must seek analysis and response formulation from the engineering group. If not, the organization runs the risk of providing an inaccurate and untimely response to the customer with serious potential detriment to customer satisfaction and loyalty. The supply chain is perennially challenged to reduce the external material cost content of products and services, through various methods including quantity buys, preferred vendor agreements, multiple sourcing, and alternative materials. When alternative materials are identified, or proposed by low cost vendors, it is necessary to assess whether the deviation from specification will have impacts to contract requirements or product performance. Supply chain must also seek analysis and approval/denial response from the engineering group. If not, the product will be held up in receiving inspection as non-conforming material – causing delays in production processes, or worse yet, the product will be in direct violation of contract requirements or unfit for purpose. When non-conforming product is identified through receipt inspection or through production quality processes, it results in a Material Review Board action which is led by a representative from the engineering department. If there is a significant sunk cost in the product, which is often the case in this business division, there is a strong motivation against making a "scrap" disposition. As such, alternative repair or refurbishment techniques must be devised, and proposed to "rescue" the parts. Regardless of the source of the suggestion, engineering is relied upon for assessing the potential impacts to product quality, performance, and conformance to contract requirements.

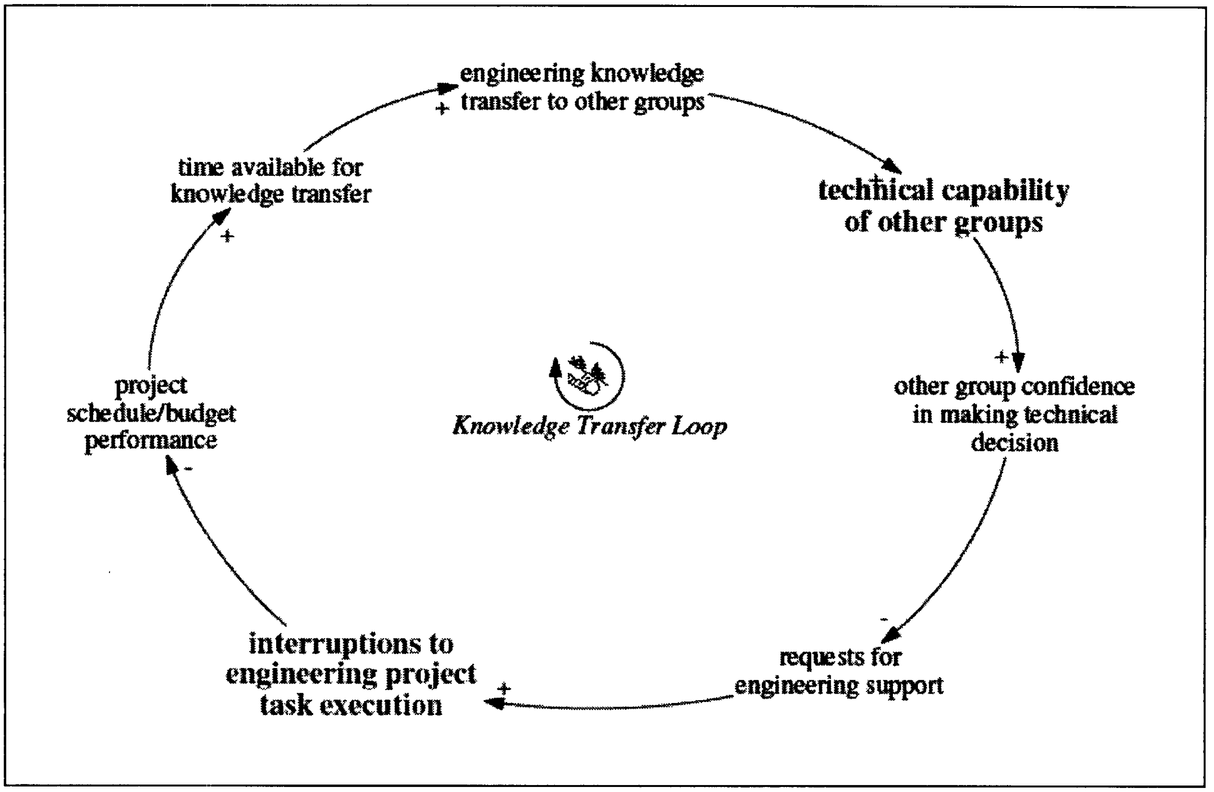


Figure 36. Engineers are the Keepers of Knowledge CLD

The CLD in Figure 36 above describes the knowledge transfer loop that, by itself, leads to the inevitable effect that technical product knowledge is consolidated in the engineering group and the transfer of knowledge to other groups is stifled. Interruptions, by negatively impacting project schedule and budget will result in schedule pressure on the engineers to not deviate from task execution efforts. As such any time originally set aside for cross-training, educational seminars, or even extended informal discussions with project managers, quality control inspectors, machine operators, and sales/marketing representatives is, instead, utilized to buttress task execution efforts. Without engineering knowledge transfer, and in the assumed absence of a motivation for other groups to seek knowledge independently, the technical capability of the other groups will stagnate. Confidence in making technical decisions will also stagnate, or decrease over time for these other groups as decision making skills "atrophy" through inactivity.

This will result in an increase in the number of interruptions to engineering project task execution as more and more technical decision making responsibility is transferred to the engineering department. The cycle continues.....ad infinitum.

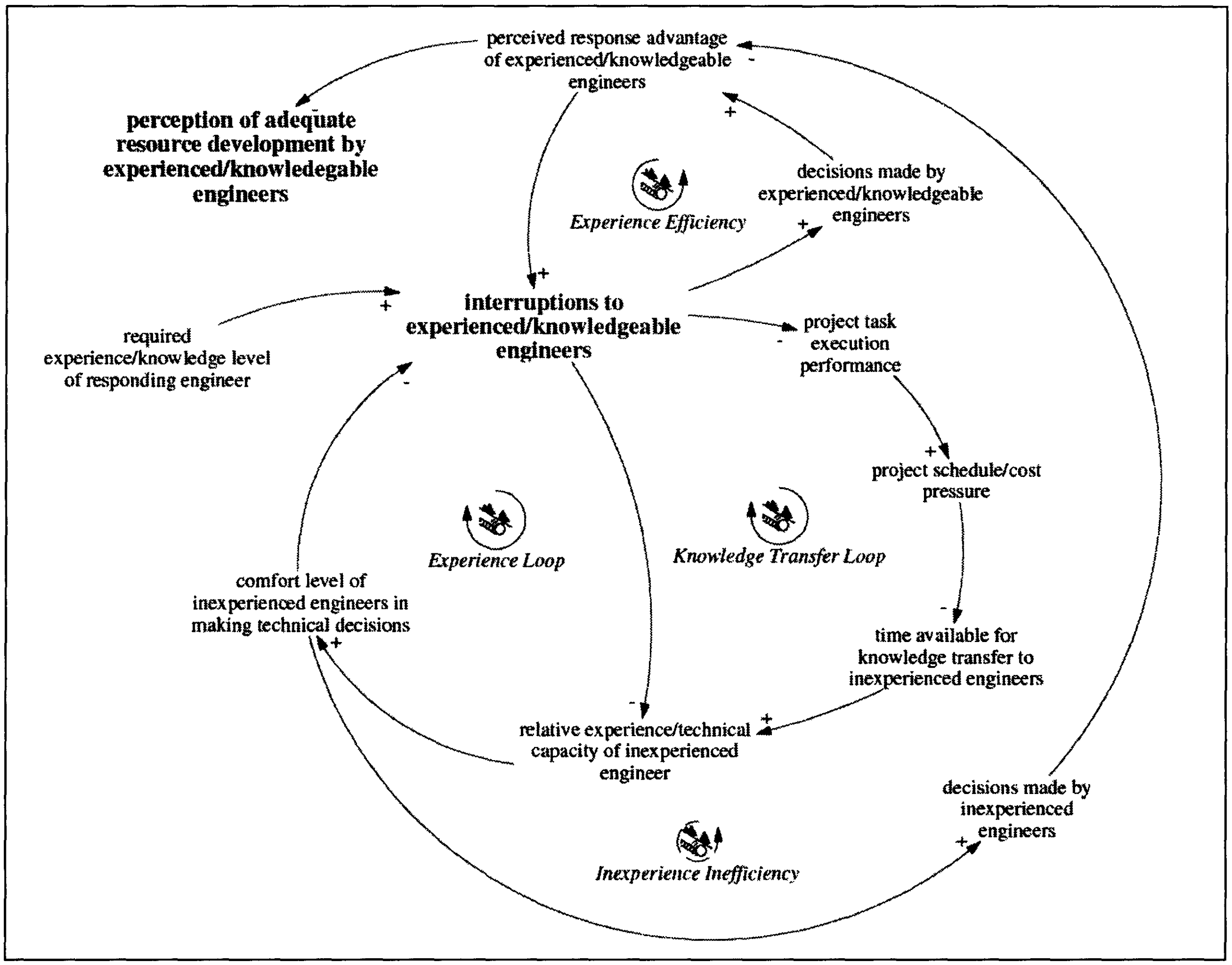


Figure 37. The Hegemony of the (Experienced) Engineer CLD

The CLD in Figure 37 above describe how experienced and knowledgeable engineers come to be viewed as uncommitted to developing inexperienced resources in the eyes of other groups. Again we find a knowledge transfer loop, but in this case it is the transfer of knowledge/experience from the experienced to the inexperienced engineers. When experienced engineers are interrupted, the by now familiar negative effect on project performance is incurred, resulting in cost/schedule pressure. Now the experienced engineer does not have the luxury of time to guide and mentor a junior engineer through a time inefficient process of making a decision for the sake of knowledge transfer, lest he resign himself to yet more pressure from project management. Instead, the experienced engineer makes the decision independently and quickly returns to his task execution process. The result is that the number of decisions made by the experienced engineers continues to increase, relative to the number of decisions made by the inexperienced engineers. The inexperienced engineers fail to grow in capability and confidence to make decisions and also end up interrupting the experienced engineers when faced with a technical decision. Externally, would be interrupters observe that the decision making is being handled by a few experienced individuals and that there is very little "bench strength" in the department. This results in a perception that the experienced engineers are not interested in developing the bench, while encouraging them to circumvent or not even address the inexperienced engineers with potential interruptions expecting them to be redirected to the experienced engineers and further exacerbating the situation.

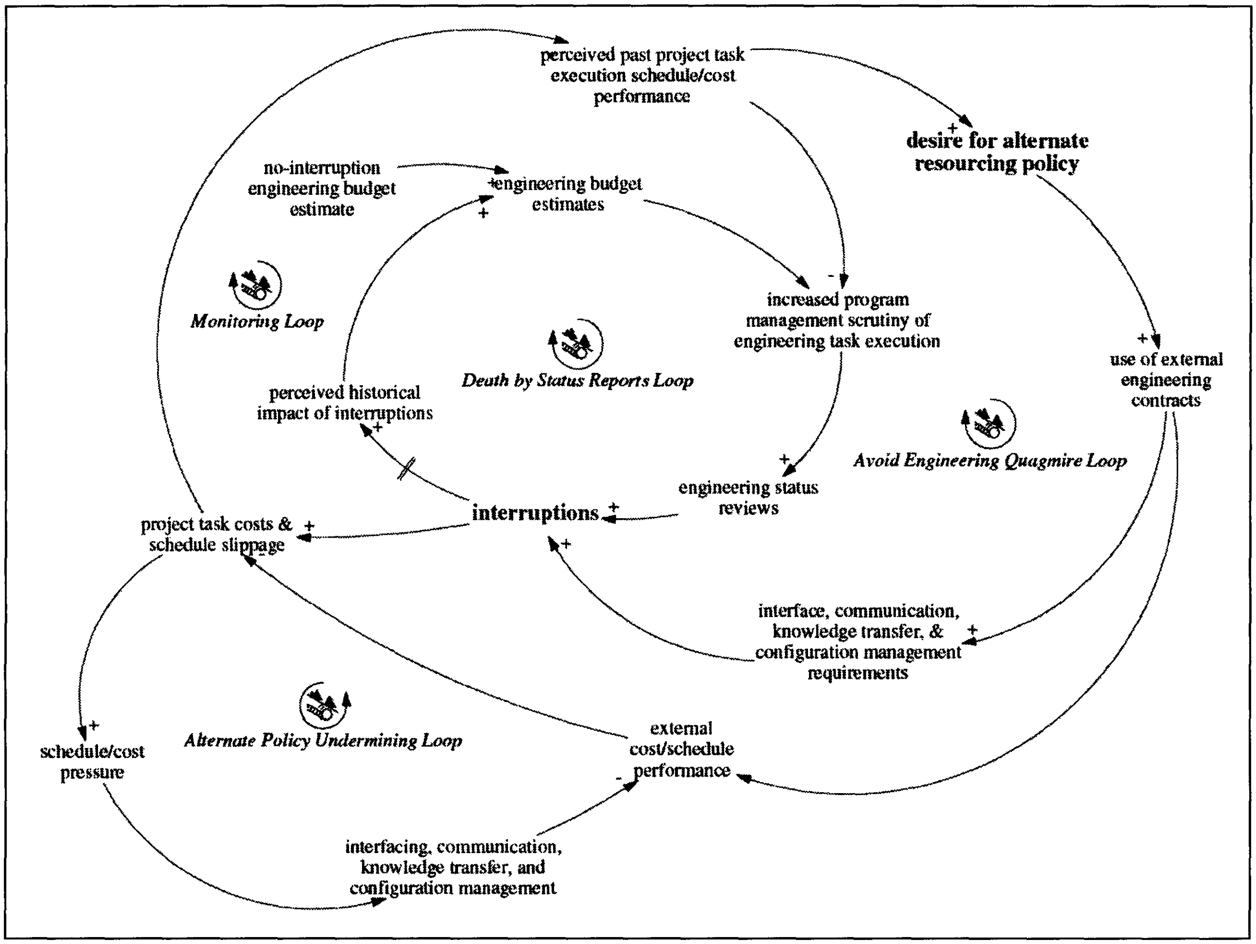


Figure 38. Always Late, Always Over Budget CLD

The CLD in Figure 38 above depicts the compounding effects interruption induced project delays and cost overruns on future delays and overruns. Engineers submit budget requests based on a scope of work, a perception of what it will take accomplish the tasks in the absence of interruption, and an expected level of interruption based on past experience. Project managers also make decisions about the level of monitoring and control they wish to implement in the project based on past project cost/schedule performance by the engineering group. Typically this will result in the proclivity of project managers to enforce stricter monitoring and controls on the task execution process such as greater number of status meetings/reports than enforced on previous projects, generating interruptions beyond the level assumed by engineering in developing budget requests. This, of course leads to greater deviations from forecasts and perhaps more draconian monitoring measures and certainly a desire to seek alternative resource options such as sub-contracted project task work. By contracting out work, an increase in "transaction" costs is incurred. In other words, to off load work effectively requires clear work scopes be written and communication/transfer of critical knowledge, interface specifications, and or configuration management requirements. This contributes once again, to unexpected interruptions to the engineers, further variance to forecast, and increased pressure to execute tasks. The lack of time results in delays in providing the work scopes, knowledge transfers, interface specifications, and configuration management requirements which undermine the ability of external resources to deliver value as expected by the project management. This further encourages program management to look outside, for means to deal with cost/schedule overruns.

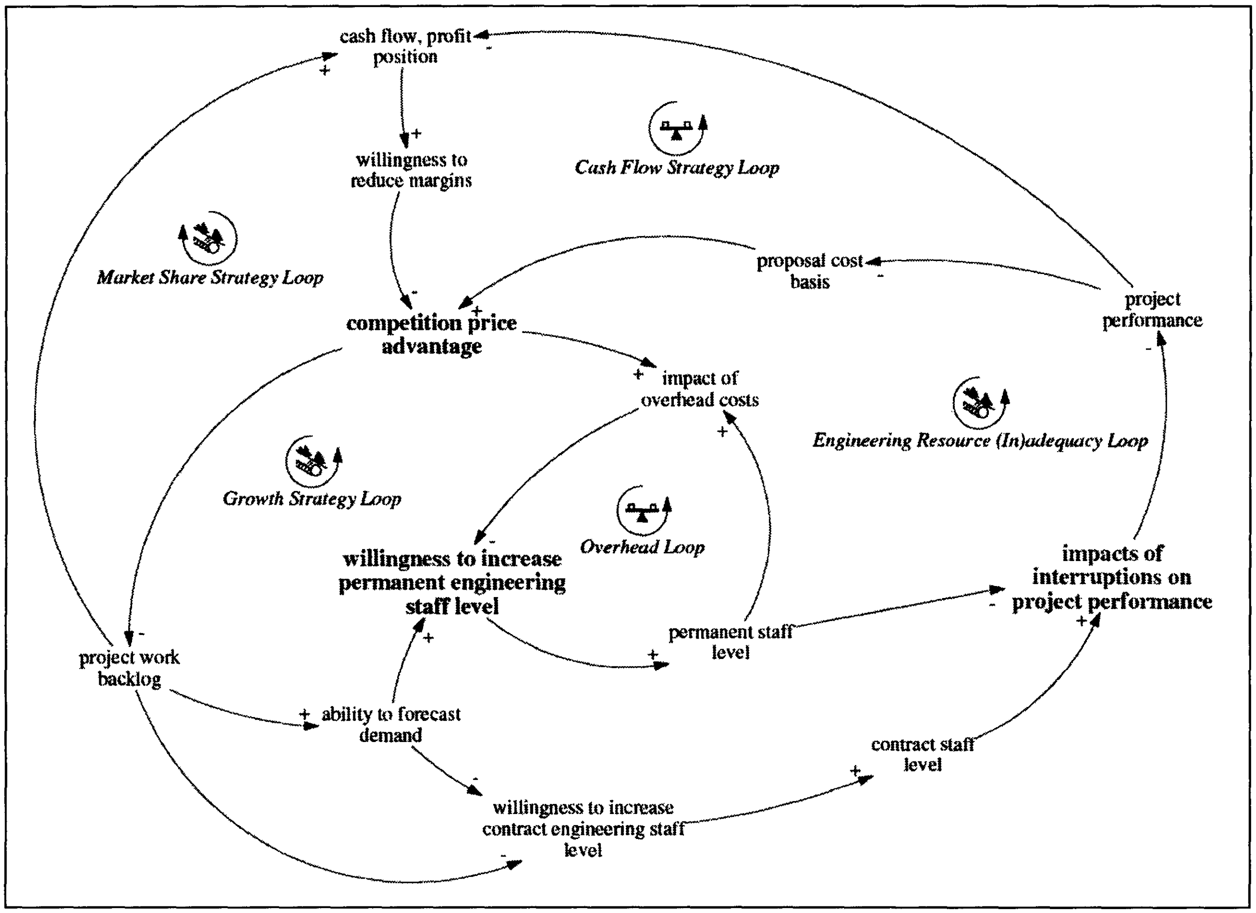


Figure 39. Stable Permanent Staff CLD

The CLD in Figure 39 above describes how the willingness to hire additional permanent engineering staff is affected by the ability to forecast demand and the competitive environment. The primary balancing loop that is of concern to senior staff is the impact of staff levels on the ability of the division to compete effectively against its competitors for greater market share, and the resulting backlogs associated with it. If the competition does not have a price advantage in the marketplace, greater project backlogs and market share can be secured, and demand forecasting becomes much less uncertain. This results in an increase in the willingness of senior management to hire permanent staff as opposed to contract staff to promote growth of the division. With more staff, the impacts of interruptions on project performance are reduced allowing tasks to be completed on schedule and under budget. This preserves and strengthens cash and profit positions of the division relative to its competitors. This, in turn, generates additional confidence by senior staff in strategic pricing decisions, and increases their willingness to operate with smaller margins, further reducing or eliminating price advantages from competitors. This seemingly virtuous cycle of growth can unfortunately be reversed in the situation where the competitor has a price advantage in an industry with strong competition for market share. In this case, the focus shifts from growth to cost control which results in reduction of willingness to hire permanent staff. Now, the impact of interruption is to compromise cost performance, and cash flow such that competitor price advantages begin to grow, further promoting the downward spiral.

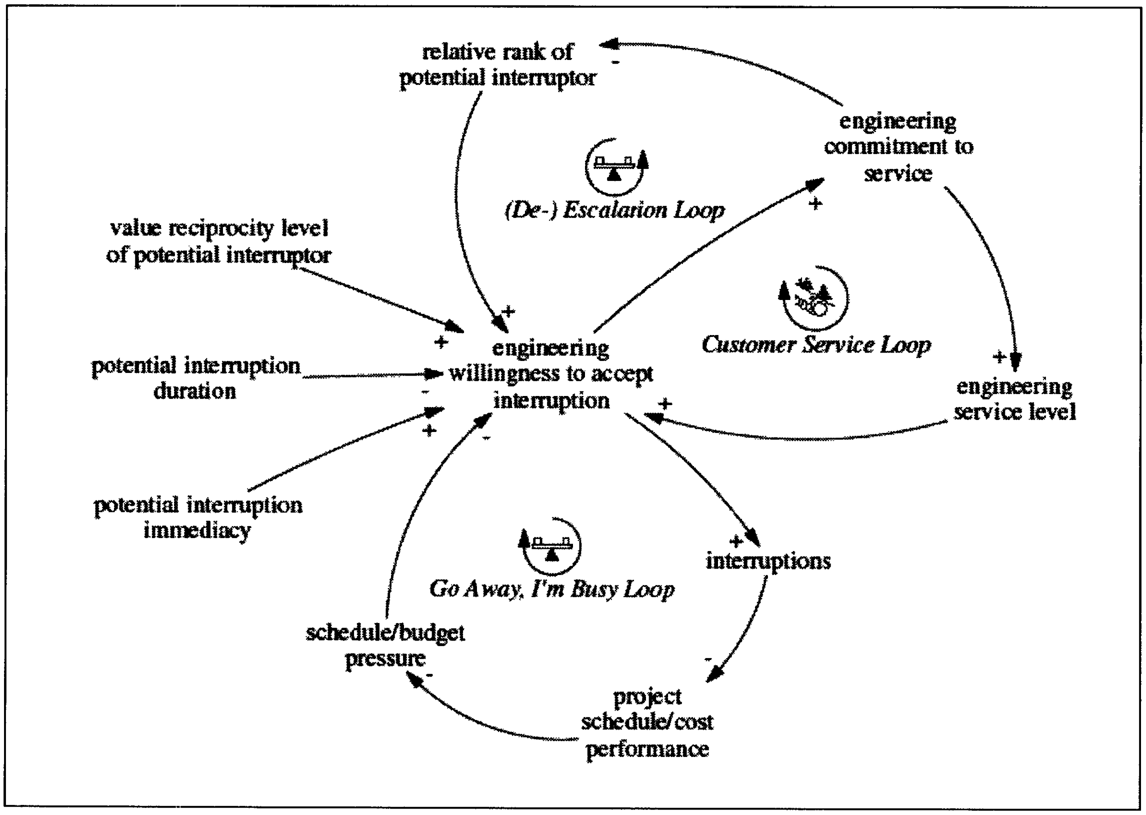


Figure 40. Helplessness CLD

The CLD in Figure 40 above depicts the facets of the engineering interruption acceptance criteria, and describes the inevitability of negative impacts from interruptions despite best of intentions and proactive policies to mitigate those impacts. The message of "internal customer service" is strong within the organization. As this is internalized by the engineering staff as a "moral imperative", the engineering service level begins to increase, with an increasing willingness to help others in need of their talents and expertise. This further reinforces the culture of service in a recursively reinforcing manner. This reinforcing customer service loop is moderated by a self-preservation mechanism – a "go away, I'm busy" loop. In this case, the negative impacts on project performance that result in increasing schedule and budget pressure result in a need to turn would be interrupters away. The other factors that affect the willingness to accept interruptions are perceived immediacy and duration of the potential interruption, and the level of reciprocity with the interrupter. If the interruption is perceived to be very small in nature, requiring only a few moments to resolve, willingness is increased. If inattention, or delay in acceptance of the interruptions is perceived to have major impacts to customer satisfaction, or financial health of the company, then willingness to be interrupted also increases. At a personal level, if the interrupter is someone who has historically provided support, or is expected to provide significant value to the engineering group going forward, willingness to be interrupted also increases. Finally, relative rank or position of the interrupter within the organization relative to the engineers will strongly influence the willingness to accept interruptions. If a member of senior staff requests a meeting, a study, a presentation, or anything else, the interruption is generally accepted as a rule. This effect of rank has the effect of neutralizing the previously described moderating effects of the "go away, I'm busy" loop. If interruptions are not accepted, or delayed significantly, this leads to a perceived reduction in commitment to service. For those groups who have come to expect (and often demand) a certain service level from engineering, this can be quite upsetting and inconvenient. The result is an escalation of the concern to supervisors, managers, and perhaps even members of senior staff, who may, in turn, issue directives to engineering to deal with the issues expediently, increasing the willingness to deal with the interruption immediately. Despite good intentions, delay and redirection policies for interruptions, eventually, the interruptions are accepted, even if begrudgingly, and the feeling of helplessness in addressing the impacts of interruption continue to escalate, while engineering resource leadership is blamed for it's inability to prevent delays and overruns.

5.3 System Dynamics Modeling & Simulation Results

A number of cause and effect relationships and feedback loops identified through the causal loop diagramming process, and in the CLD's described above were used as the basis for building a formal system dynamics model. A description of the system dynamics model itself, as well as the results of the simulations executed with the model will be provided in the sub-sections that follow. A complete listing of model equations is contained in Appendix A.

5.3.1 System Dynamics Model Description

The system dynamics model developed as part of the current research is comprised of five "components":

- Basic Financial Indicator Model
- Project Execution Model
- Project Status Model
- Interruption Management Policy Model
- Engineering Performance Indicators Model

The heart of the basic financial indicator model is presented in Figure 41 below. An initial stock of cash is depleted as project work is done and augmented by periodic inputs of cash from milestone payments. A running profit margin based on the initial cash position for the project and the budgeted project cost is also modeled. The cash is considered the cash associated with the project task execution process only and does not include affects on cash from upstream (e.g bid & proposal) or downstream (e.g. production and aftermarket).

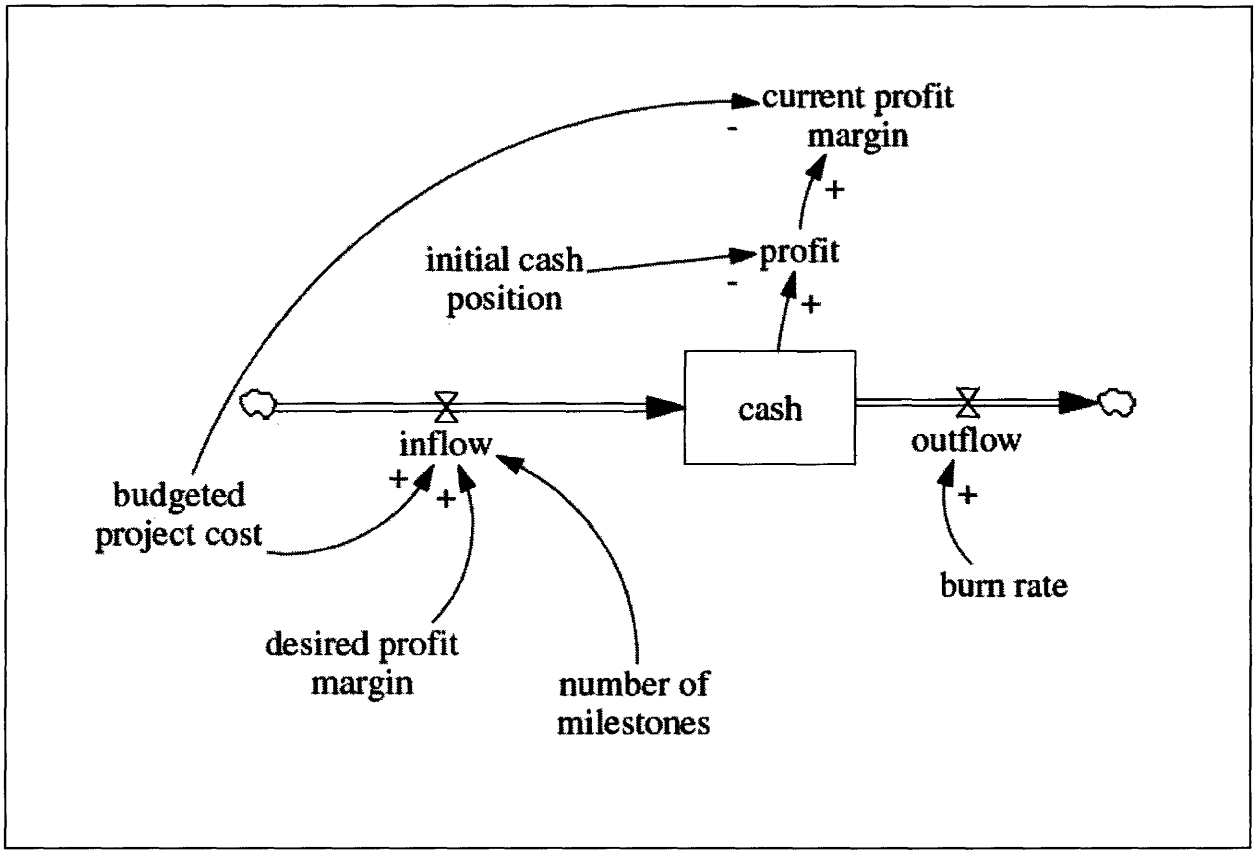


Figure 41. Basic Financial Indicator Model

In order to implement a periodic infusion of cash from milestone payments, the basic model was augmented with mechanisms to capture the real world, discrete behavior, given the number of milestones and the percent complete triggers for issuance of invoices. Delays from invoicing to payment were not implemented as part of the model. The complete financial indicator model is depicted in Figure 42 below.

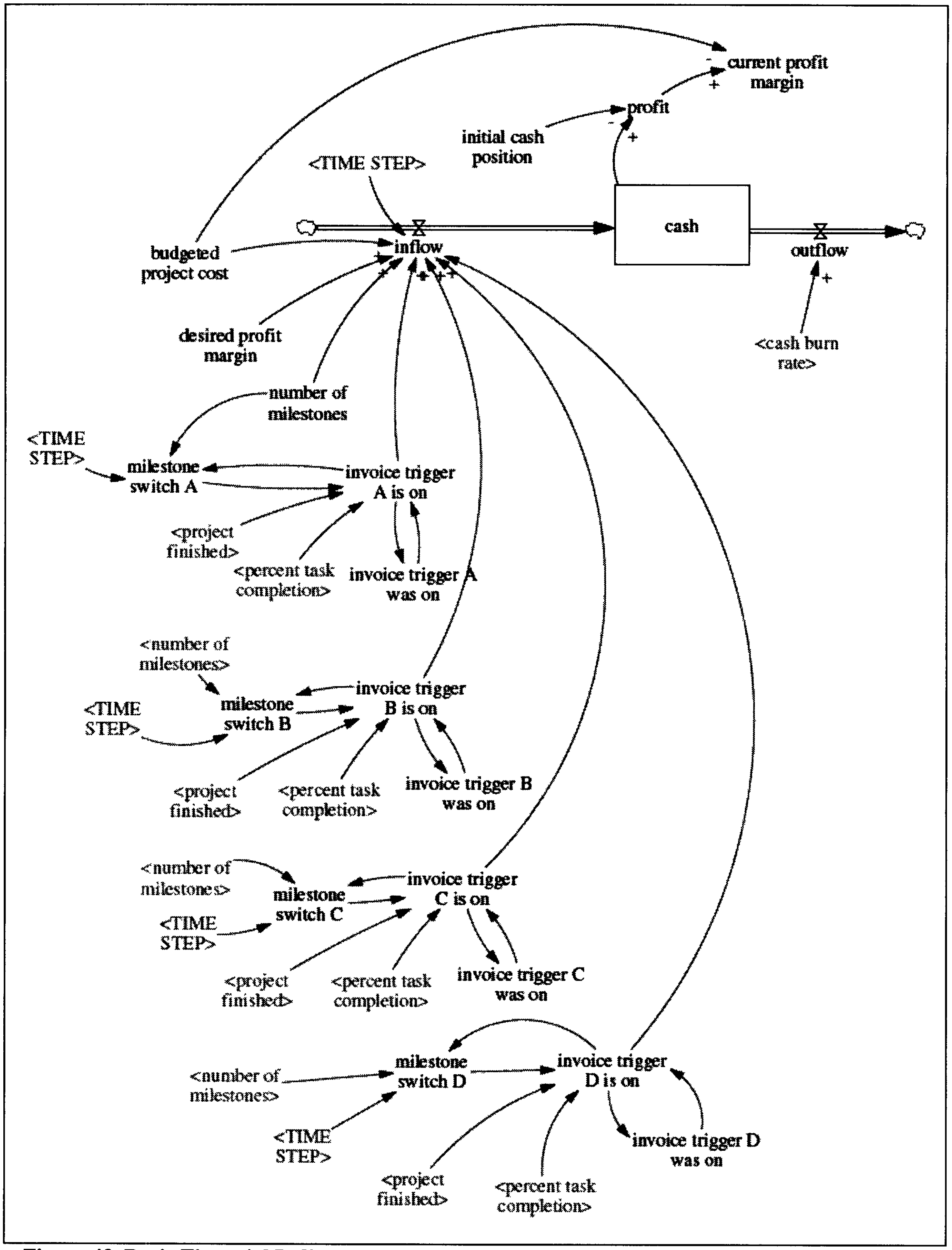


Figure 42. Basic Financial Indicator Model with Triggers to Discrete Milestone Billing/Payment

The project execution model and the project status model were adapted from the classic project rework cycle formulation developed by Cooper (Cooper 1980; Cooper 1993)and used widely in educational coursework and product development research with system dynamics. Project task execution is governed by the stock-flow structure seen in Figure 43 below. Task accomplishment is based on the rate at which tasks are accomplished correctly, and the rate at which tasks are accomplished incorrectly (or need to be reworked for other reasons) becoming tasks that are returned to the stock of what is left to do once they are discovered. The fraction of tasks which turn into rework versus the fraction that are completed correctly, is primarily influenced by the quality of the work being done. The quality, in the current research is affected by the schedule pressure. The rate of working is affected by the productivity and the number of resources that are applied to the tasks.

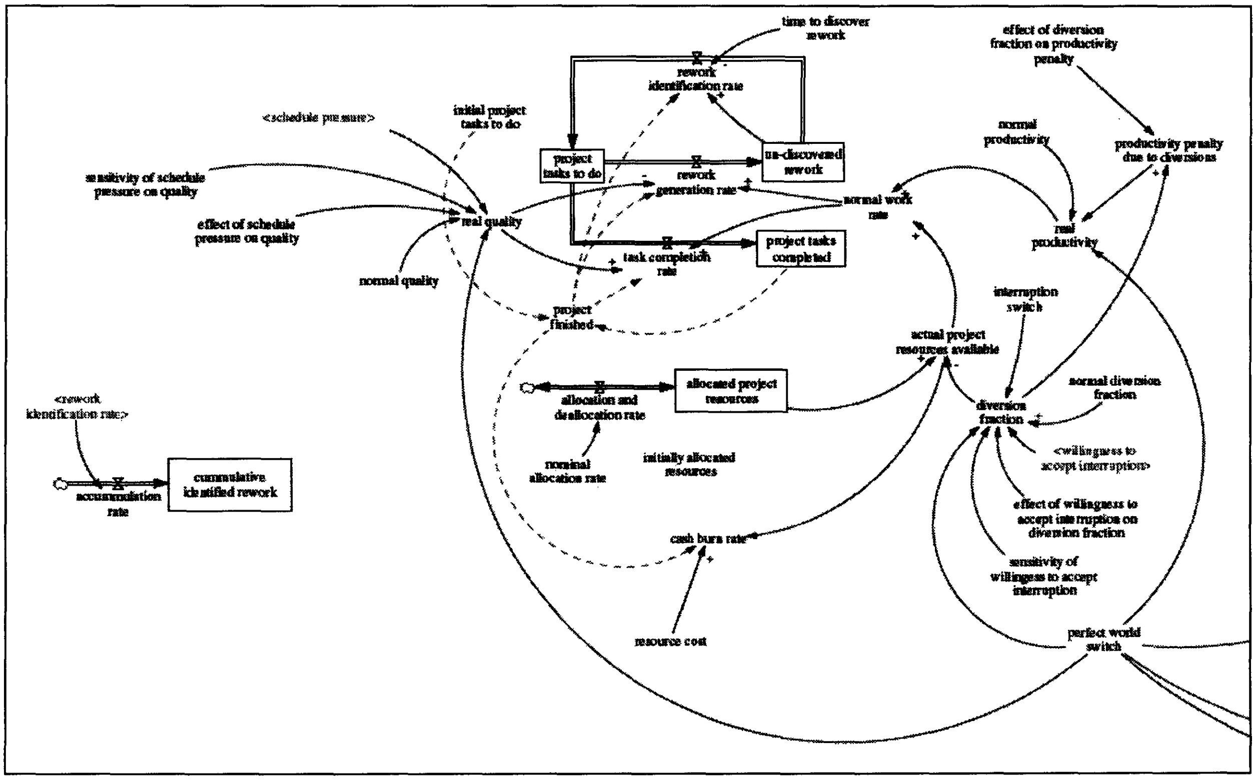


Figure 43. Project Exectution Model

In the current research, the productivity was modeled as the normal productivity (i.e. the productivity of resources operating in environment where there are no interruptions), and an effect of diversions on that normal productivity. In this case interruptions are expected to result in an "inefficiency" caused by a cognitive reset to get back to the same place an engineer was before an interruption. In addition to the effect on productivity, the interruptions also have a direct impact on the effective number of engineering resources that are working on project tasks. These interruptions are modeled in the aggregate as an average diversion fraction. The diversion fraction is affected by the willingness of engineers to accept interruptions based on the policy model to be described later. The effects of schedule pressure on quality, the effects of diversion fraction on productivity, and the effects of willingness to accept interruptions on the diversion fraction are input as (normalized) table functions. Depicted in Figures 44, 45, & 46 below, these effects are based (qualitatively) upon personal experience, validated by opinions received during follow up interviews.

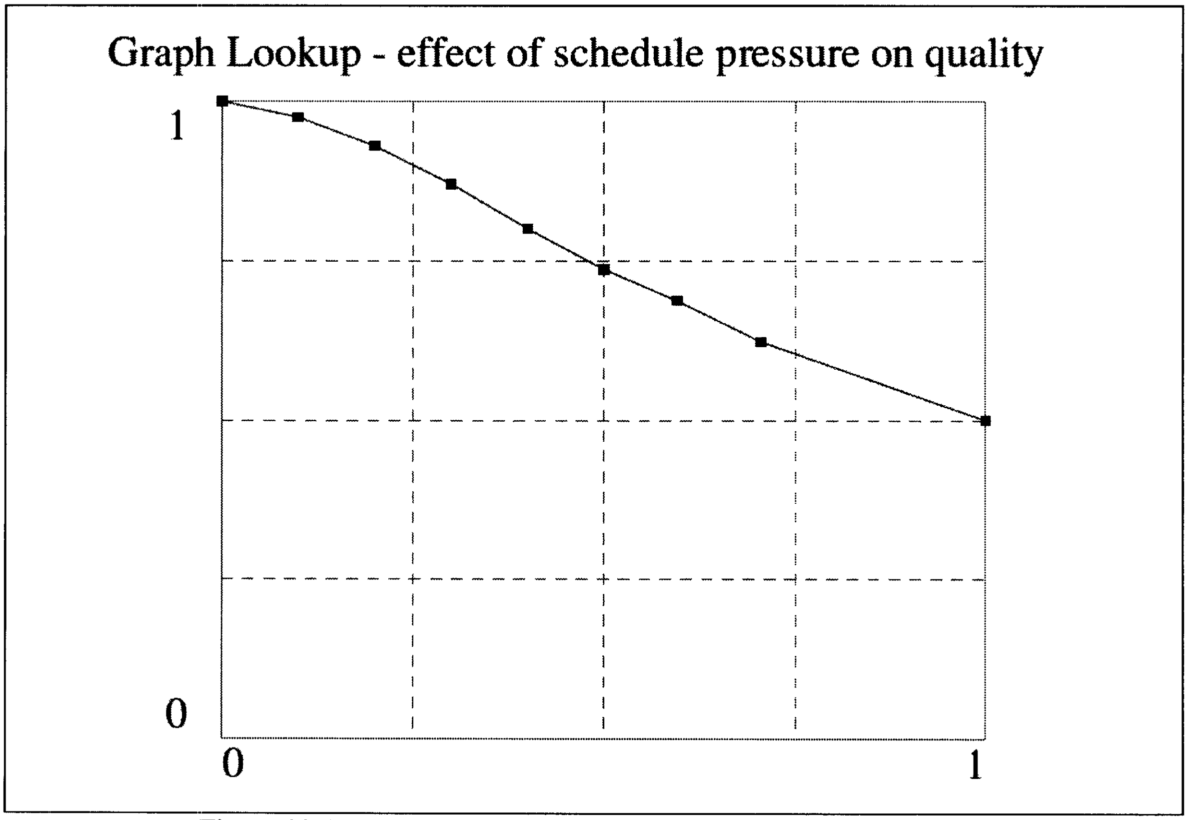


Figure 44. Look-Up Function: Effect of Schedule Pressure on Quality

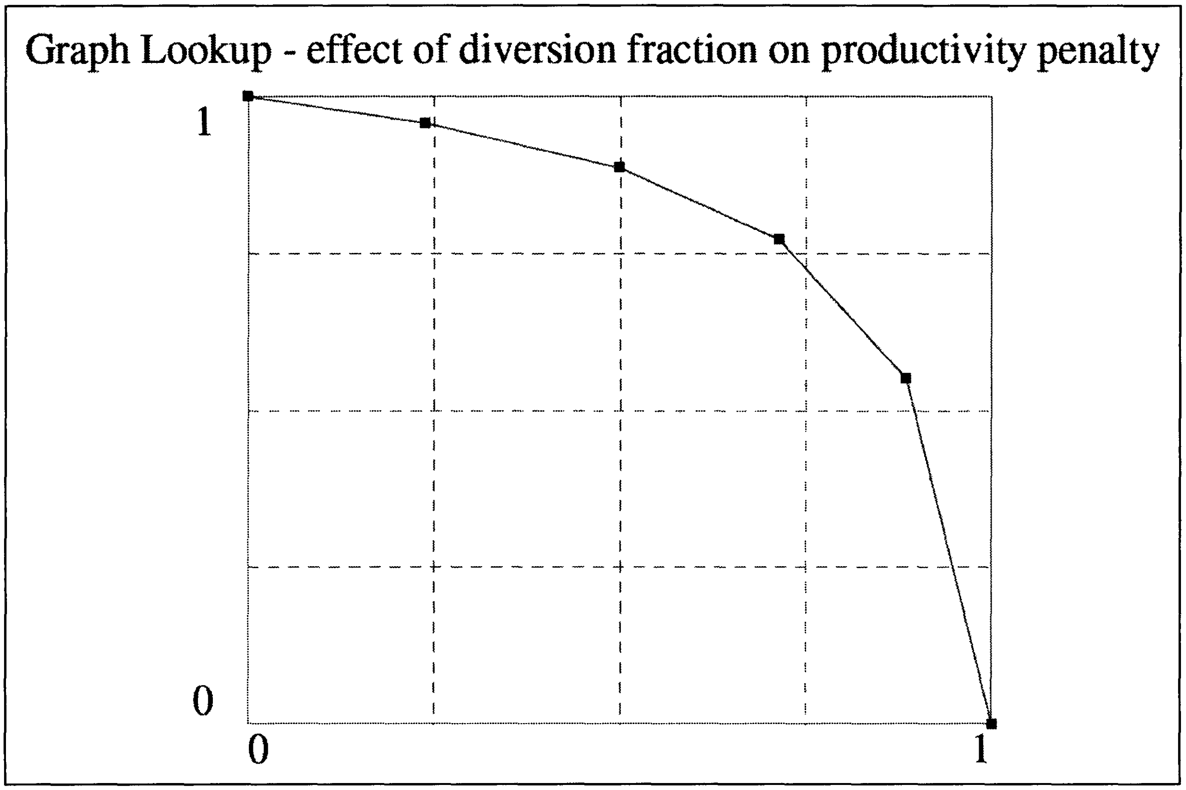


Figure 45. Look-Up Table: Effect of Diversion Fraction on Productivity Penalty

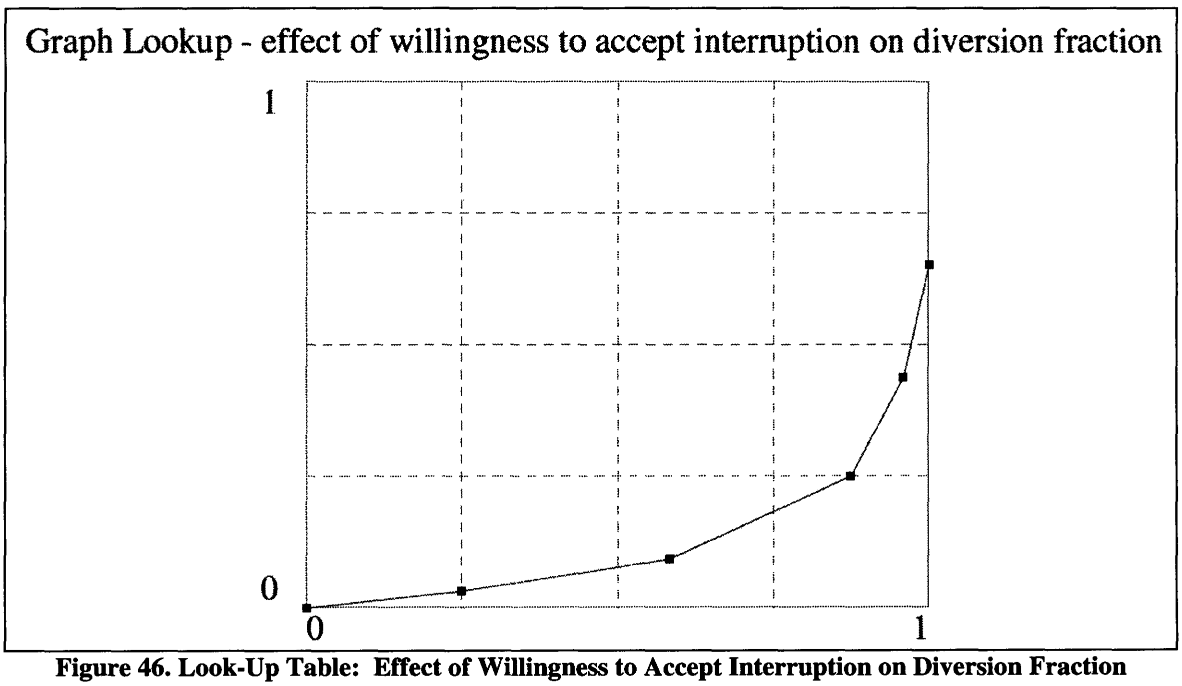


Figure 46. Look-Up Table: Effect of Willingness to Accept Interruption on Diversion Fraction

The project status model was adapted, once again from the well known project task execution model, and simplified for the purpose of the current research. The model calculates several "typical" parameters that are used by project management professionals to track the cost/schedule status for a project. These parameters are then used to update perceptions of progress to date and projections to the end of the project. Figure 47 below depicts the parameters of this component.

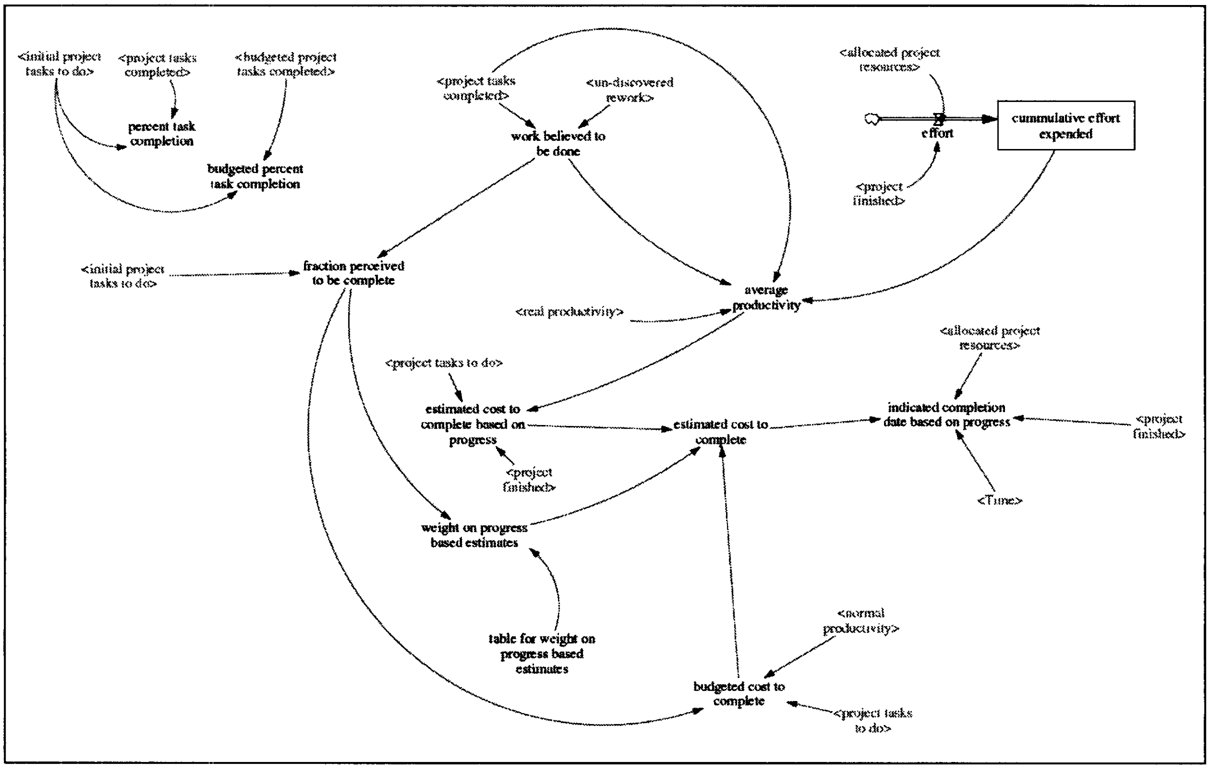


Figure 47. Project Status Model

The results of the interviews, network analyses, and CLDs were used to formulate a model of engineering resource interruption management policy. Figure 48 below depicts the policy component. The purpose of this component is to determine the willingness of engineering to accept interruptions, which is then used in the project task execution component, with cascading effects throughout the entire system dynamics model.

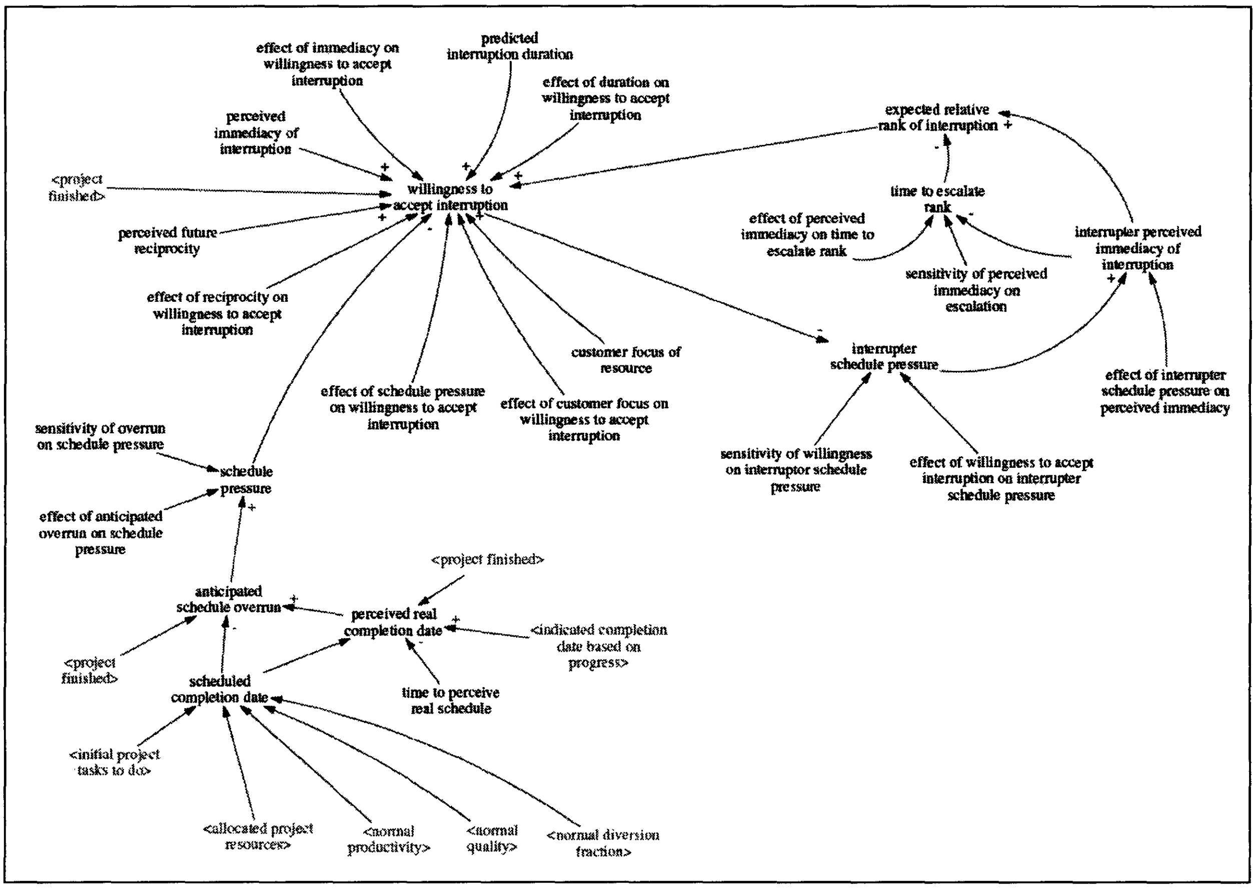


Figure 48. Interruption Management Policy Model

The willingness to accept interruption is modeled so as to be affected by the following six factors primarily:

- Rank of Interruption
- Perceived Duration of Interruption
- Perceived Immediacy of Interruption
- Customer Focus
- Perceived Future Reciprocity
- Schedule Pressure

The rank of interruption is a measure of the relative position of power/influence of the interrupter within the organization relative to that of the engineering resources. For example, if a quality control inspector comes with a request for service (i.e. an interruption) the willingness to interrupt will not be as high as if a member of management or senior staff has a request. However, if interruptions are refused, this has the effect of potentially impacting the schedule pressure and perceived immediacy of the individual requesting the interruption. This, in turn, leads to an escalation process whereby the original interrupter goes to his or her manager and indicates that they are unable to obtain sufficient service quality from engineering, which leads to a re-request for support (i.e. a new interruption) with a higher rank level than the previous one. Eventually, the relative rank becomes high enough that the interruption is accepted without delay.

If a potential interruption is perceived to require very little effort and therefore very little time to resolve, then the engineering resource is more willing to accept the interruption. If the interruption is much longer in duration, with a visible and sustained impact on short term productivity, it may be refused, redirected, or delayed until some future time.

If an interruption is perceived to be urgent in nature, this will also tend to increase the relative immediacy of interruption. For example, if signoff of a quality non-conformance is required to ship a product on time, or if a component with some sort of non-conformance is holding up production pending a disposition from engineering, the engineer is more likely to accept the interruption.

The degree to which engineers are "customer focused" is also a factor in the willingness to accept interruption. In other words, the degree to which engineers perceive their roles as service providers within the organization tends to increase willingness to help others in need. This is fostered both by internal commitment/beliefs, as well as corporate visions and objectives that help to shape the culture of the organization as well.

At an interdepartmental, or even personal level reciprocity also plays a role in willingness to accept interruptions. This may be thought of as the "what have you done for me lately" factor. If there is a perception that the exchange of support, service, information, or value (generically) is one-way, from the engineer to the interrupter, then willingness is decreased. If the perception is balanced, or tipped in the favor of the engineer, then willingness can be expected to increase.

Finally, schedule pressure plays a significant role in willingness to accept interruptions. In many respects, this is a "self-preservation" factor. As the time demands become heavier, project schedules and budgets begin to overrun, and more attention and focus by management are applied to task execution, engineers will tend to defer or redirect interruptions more readily. This is perceived to be the only course of action in order to preserve productivity.
The two factors which play the largest role, rank and schedule pressure are the greatest. Rank, from a practical perspective, tends to be "binary" in nature. If the interruption is from a supervisor, or manager, the interruption is generally accepted. If the interruption is from someone at a comparable or lower rank, then rank does not play a role in the willingness. Schedule pressure, as a self preservation policy, is heavily weighted in the formulation for willingness. In the model formulation, and as shown in Figure 49 below, schedule pressure was given an 80% weighting, with the balance 20% divided equally among the other factors. This weighting, and the effect to rank was consistent with the comments and observations obtained from follow up interviews with heavily interrupted engineering resources at the company.

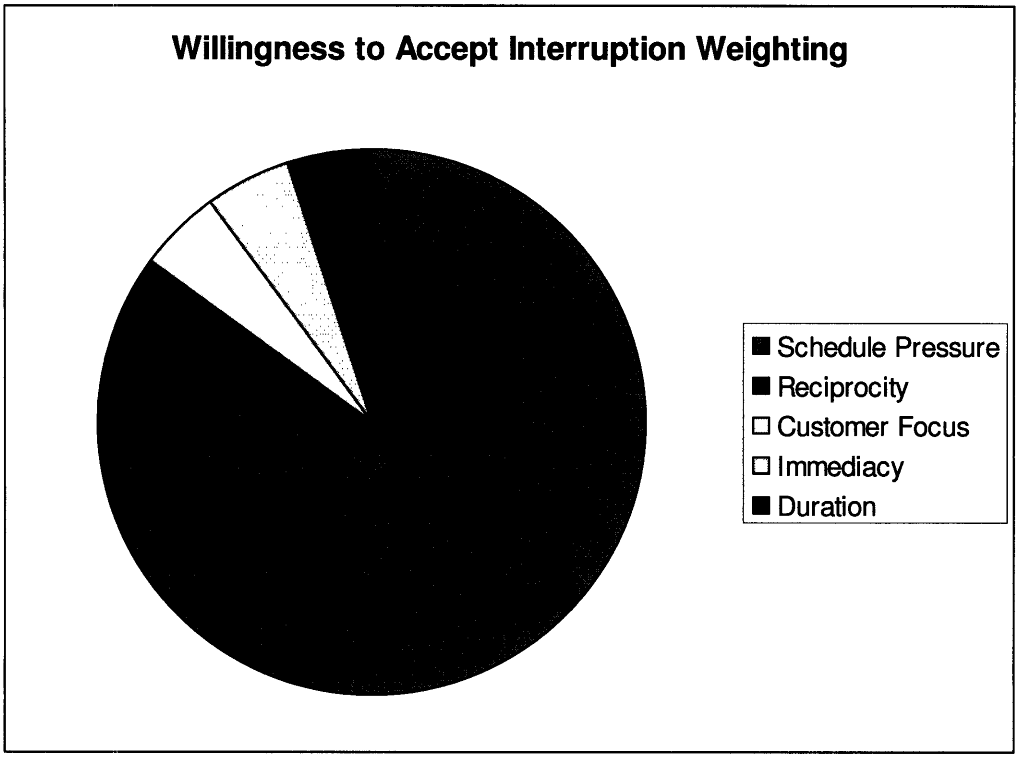


Figure 49. Weighting of Factors Influencing Willingness to Accept Interruption

The influence of the individual factors is modeled via a look-up table function in Vensim©. Figures 50 below depicts the effect of anticipated schedule overrun on schedule pressure, while figures 51-57 provide graphs of the tables of effects of the major players (not including rank) on the willingness to accept interruption.

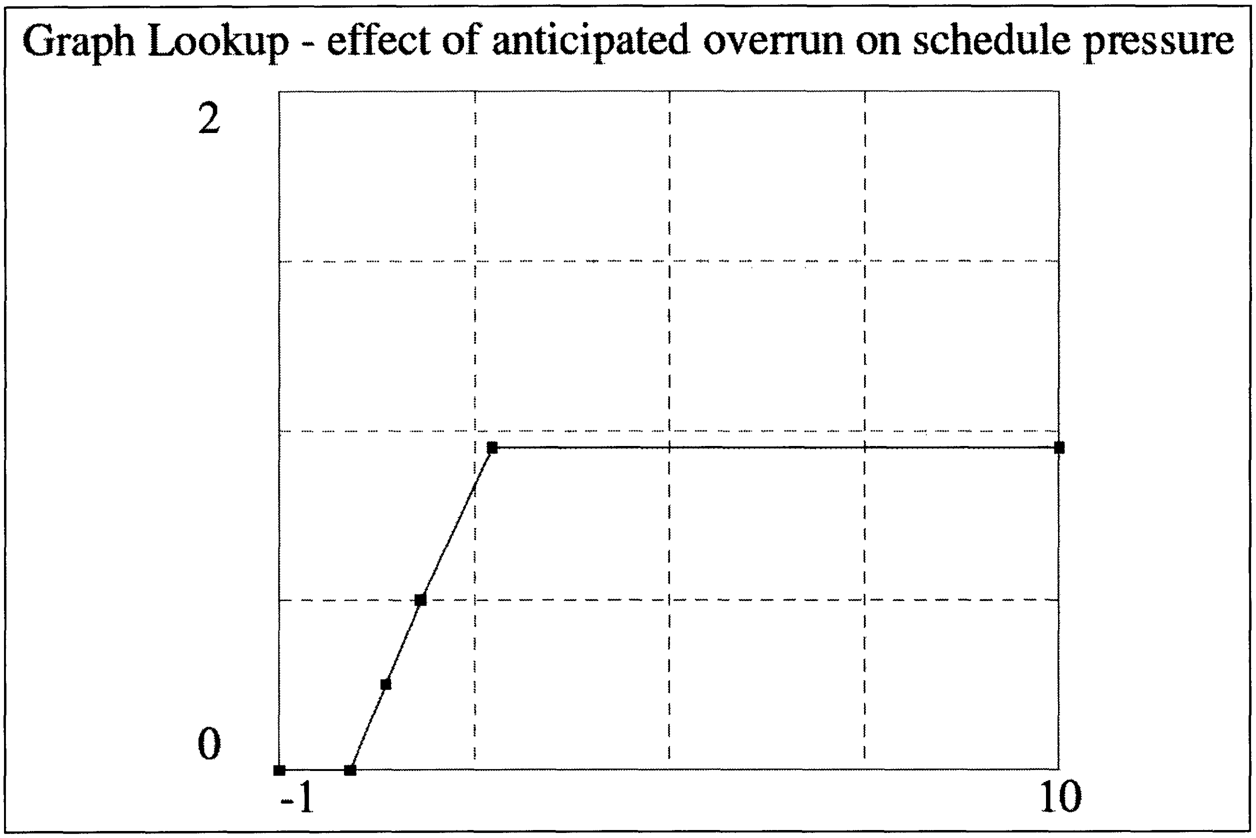


Figure 50.Look-Up Table: Effect of Anticipated Schedule Overrun on Schedule Pressure

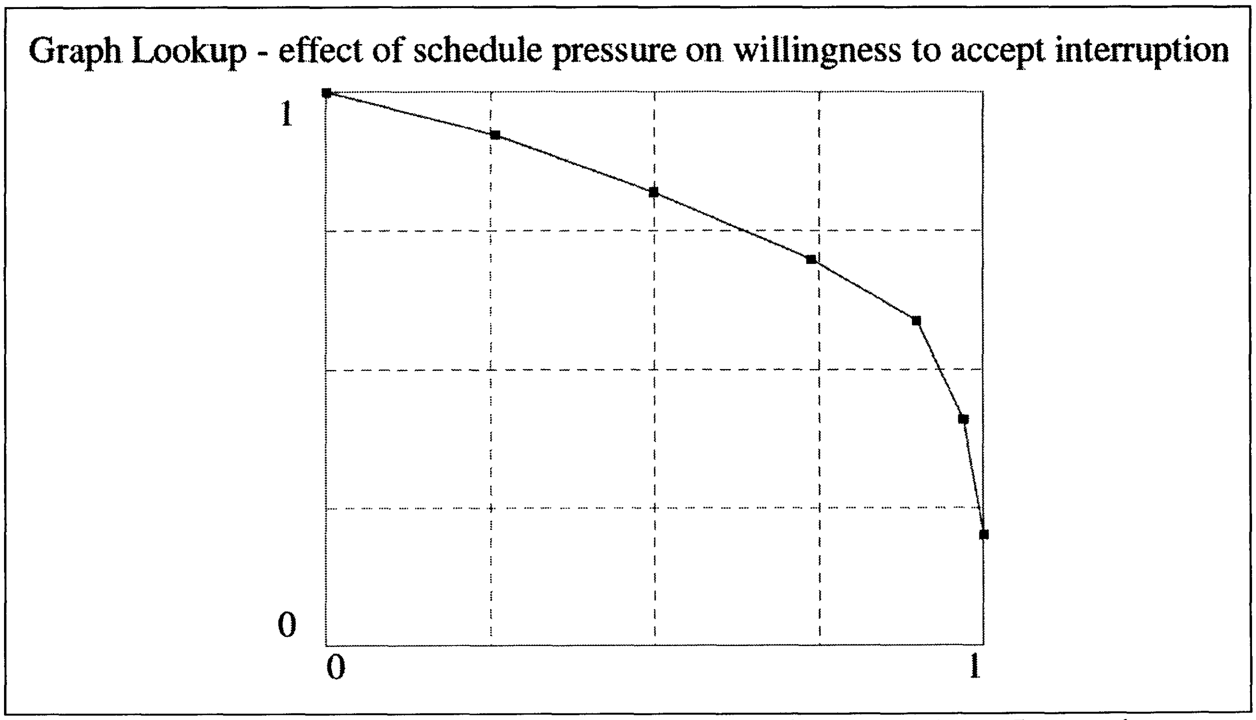


Figure 51. Look-Up Table: Effect of Schedule Pressure on Willingness to Accept Interruption

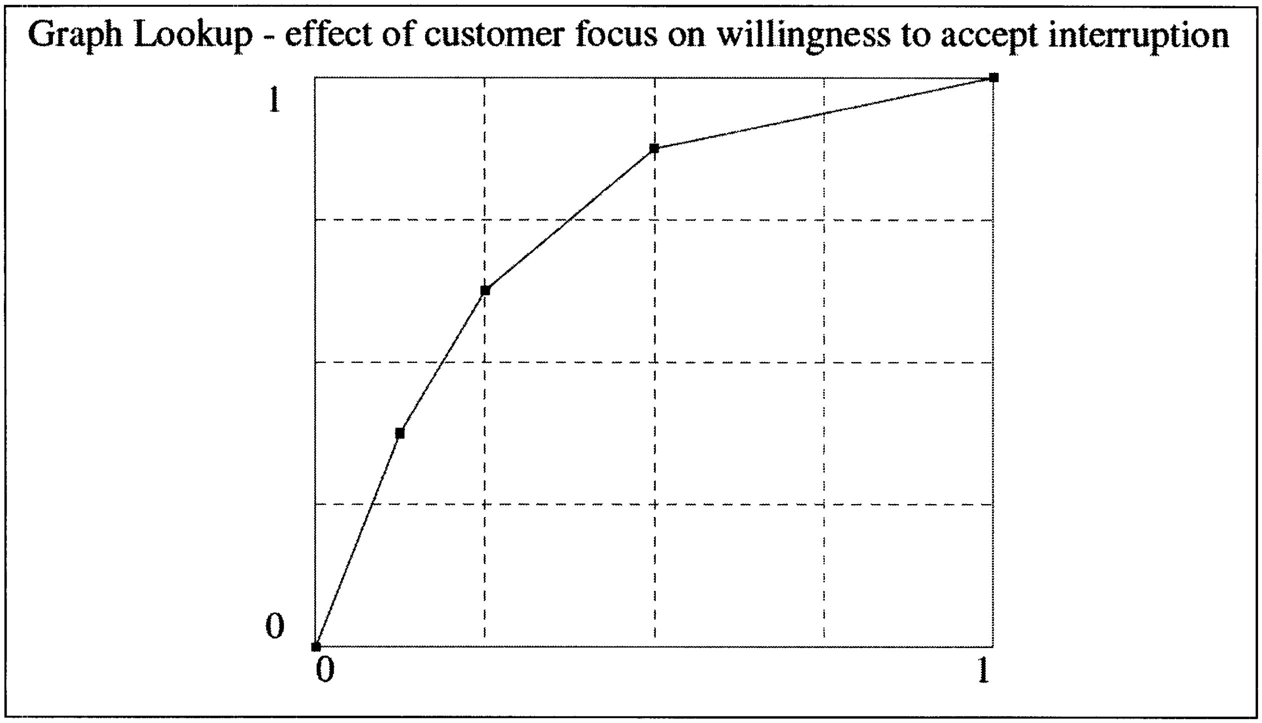


Figure 52. Look-Up Table: Effect of Customer Focus on Willingness to Accept Interruption

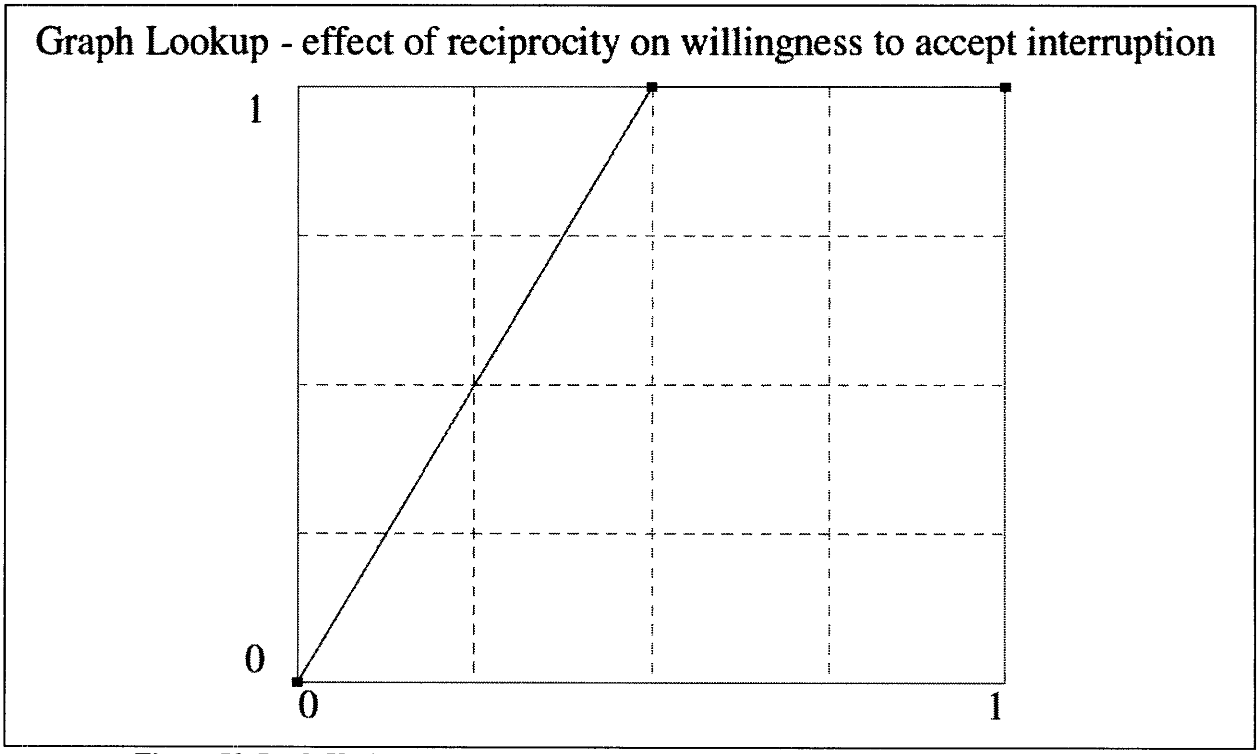


Figure 53. Look-Up Table: Effect of Reciprocity on Willingness to Accept Interruption

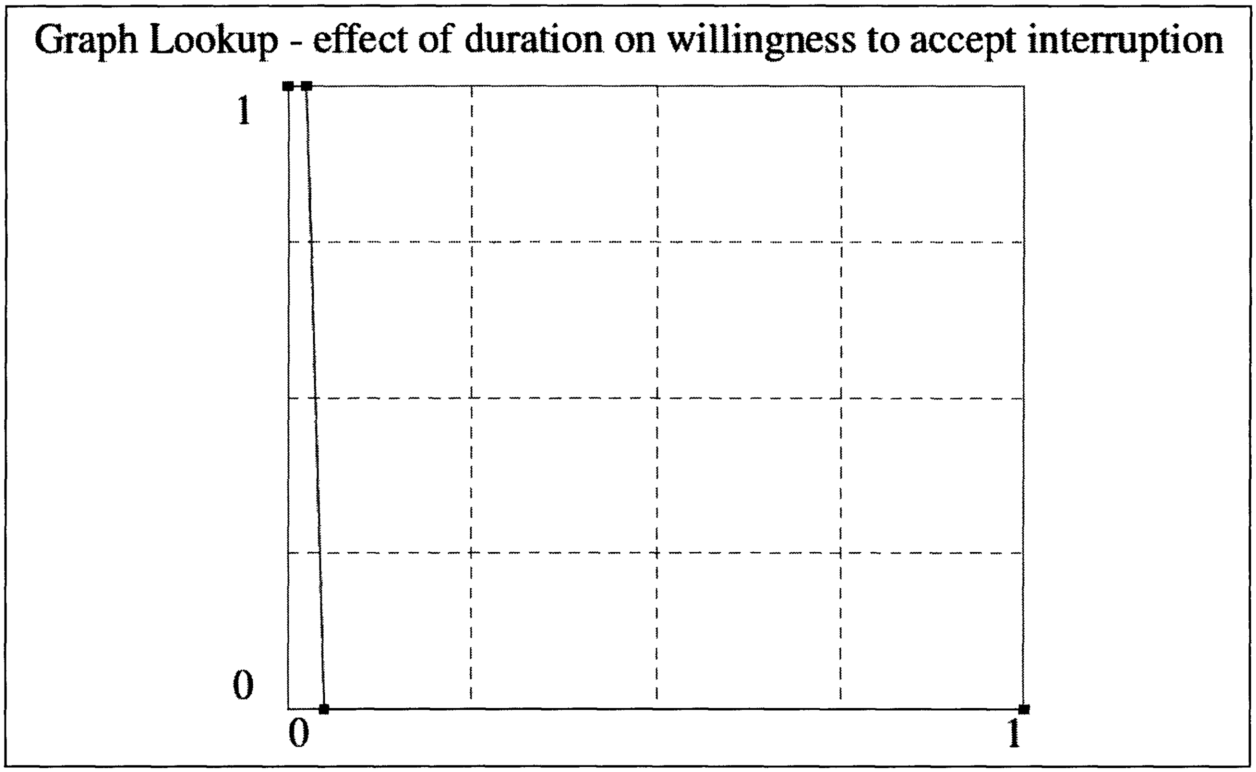


Figure 54. Look-Up Table: Effect of Duration on Willingness to Accept Interruption

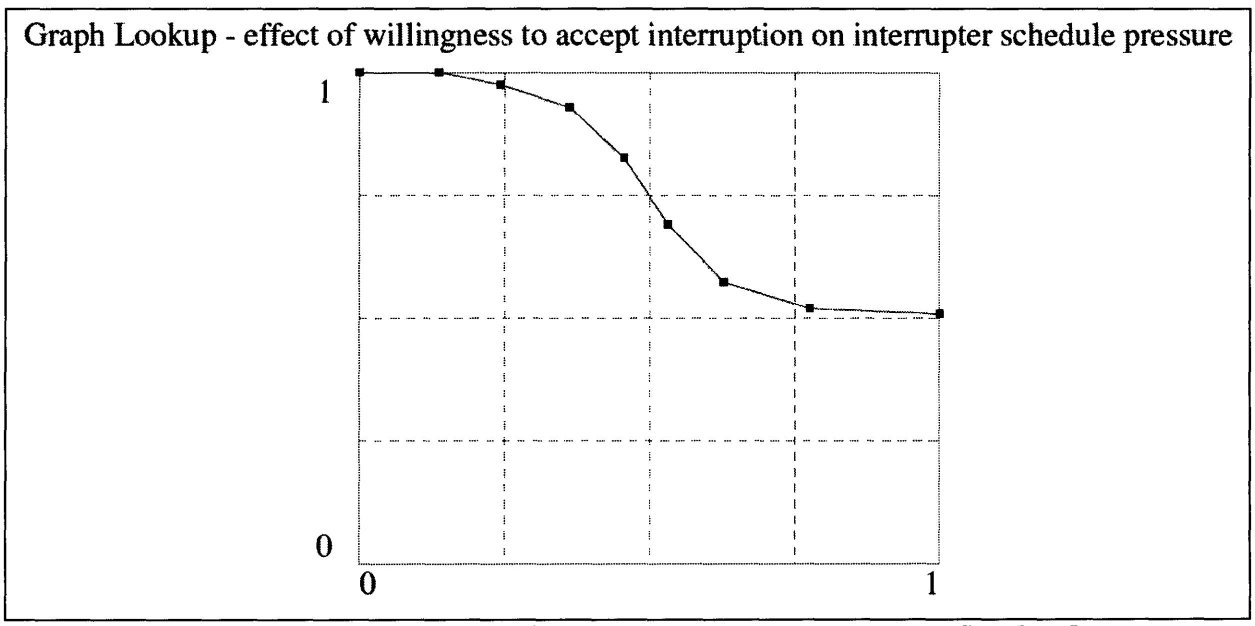


Figure 55. Look-Up Table: Effect of Willingness to Interrupt on Interrupter Schedule Pressure

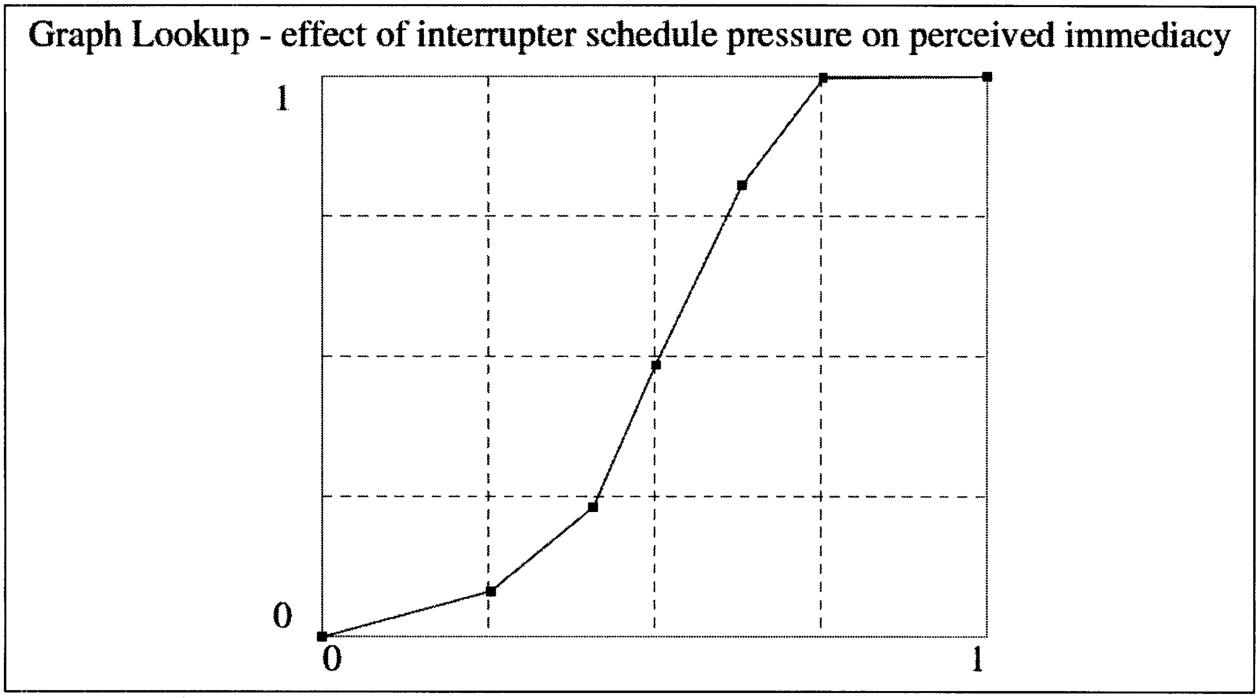


Figure 56. Look-Up Table: Effect of Interrupter Schedule Pressure on Immediacy

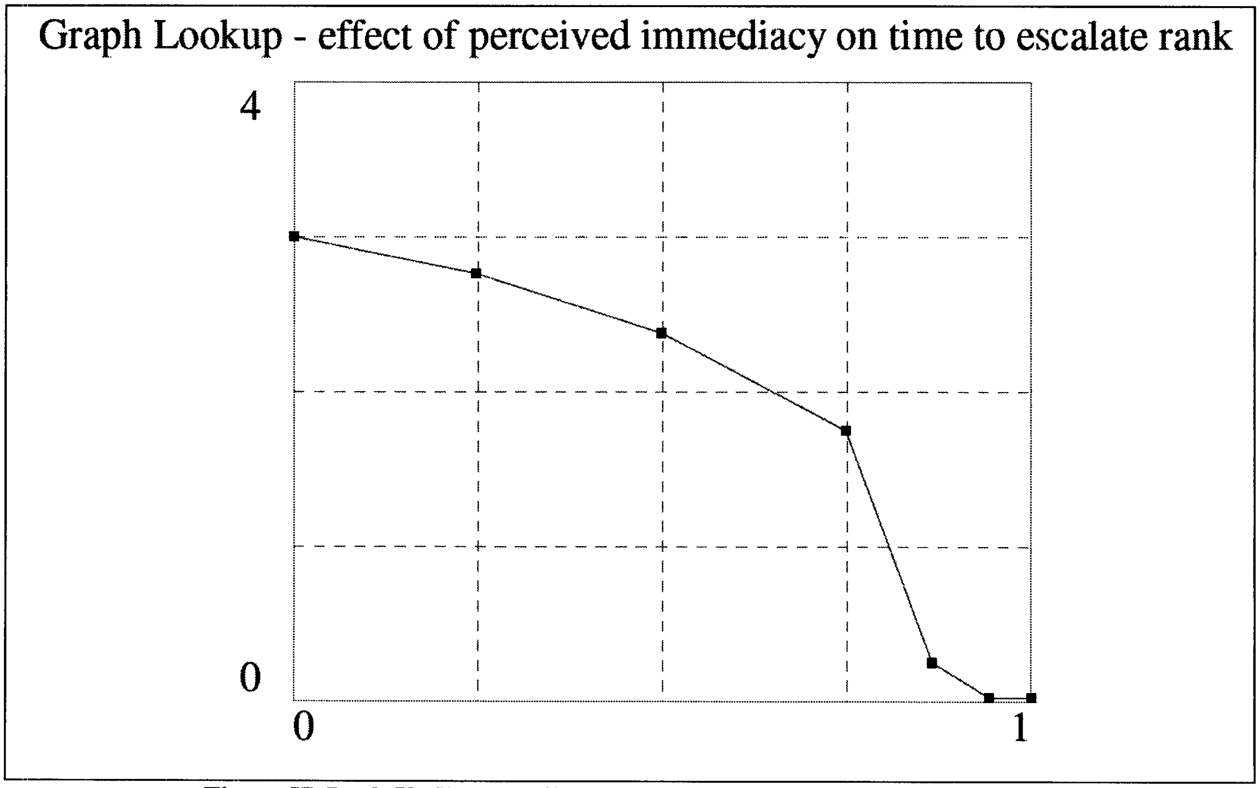


Figure 57. Look-Up Table: Effect of Immediacy on Time to Escalate Rank

The final component of the system dynamics model is the engineering performance indicators. This is the portion of the model that seeks to identify the effect over time on the high level goals of the engineering organization as formulated by management. In the model a weighted performance factor was created that summed the contributions from “on time”, “under budget”, and “right the first time” factors. This weighted performance factor was used to determine an aggregate engineering performance index (EPI). Another factor was developed, tracking the perception of engineering as focused on customer service or as a “team player” based on schedule pressure and perceptions of interrupters. This factor is the engineering perceived service quality (EPSQ). Finally the EPI and EPSQ were used to define an engineering hopelessness index (EHI) which serves as a proxy of frustration level of engineering resources based on inability to improve project task execution performance or service quality levels, despite their best efforts.

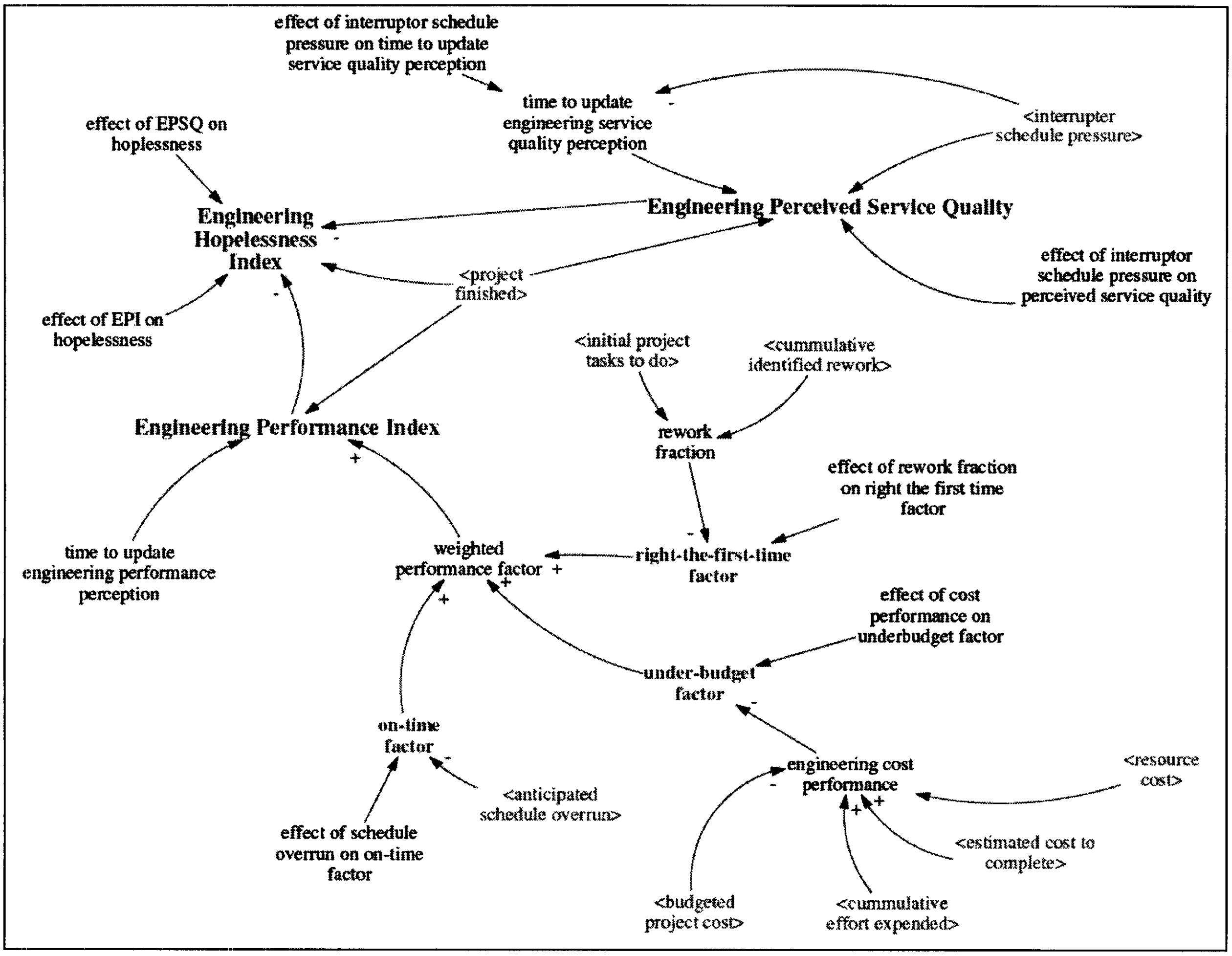


Figure 58. Engineering Performance Indicators Model

Figure 58 above depicts the engineering performance indicators component of the system dynamics model. EPI and EPSQ were weighted equally in the determination of EHI, as depicted in Figure 59 below. On-time, under-budget, and right-the-first-time factors were also weighted evenly in the formulation of EPI. This is depicted below in Figure 60.

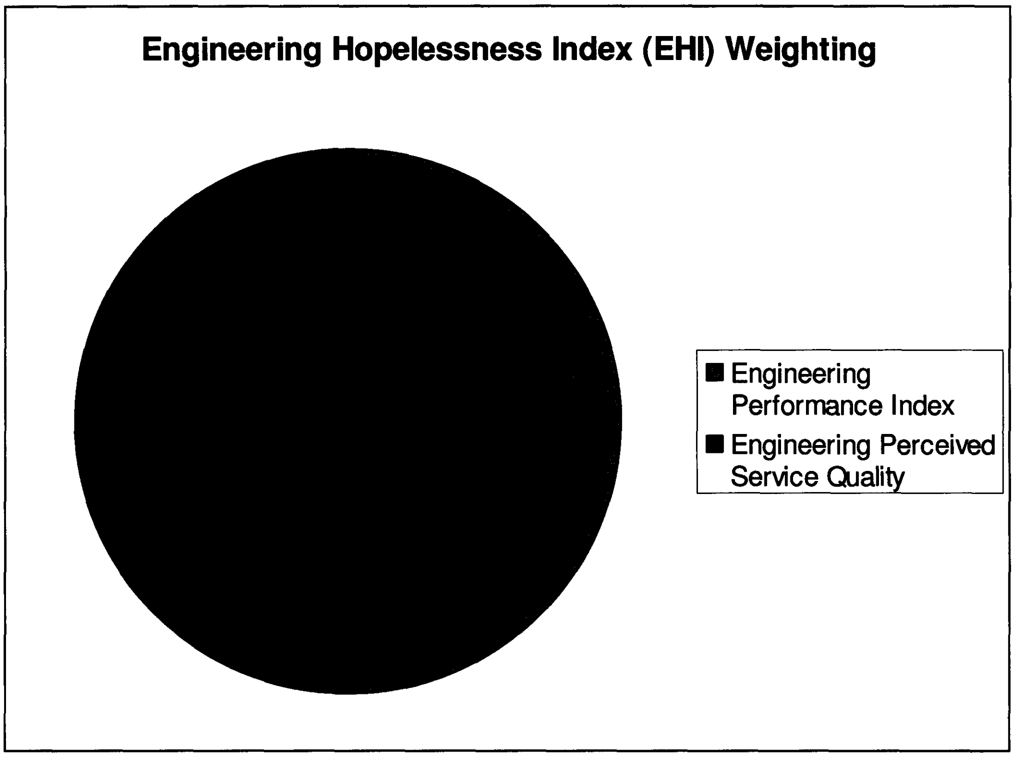


Figure 59. Weighting of EPSQ and EPI on EHI

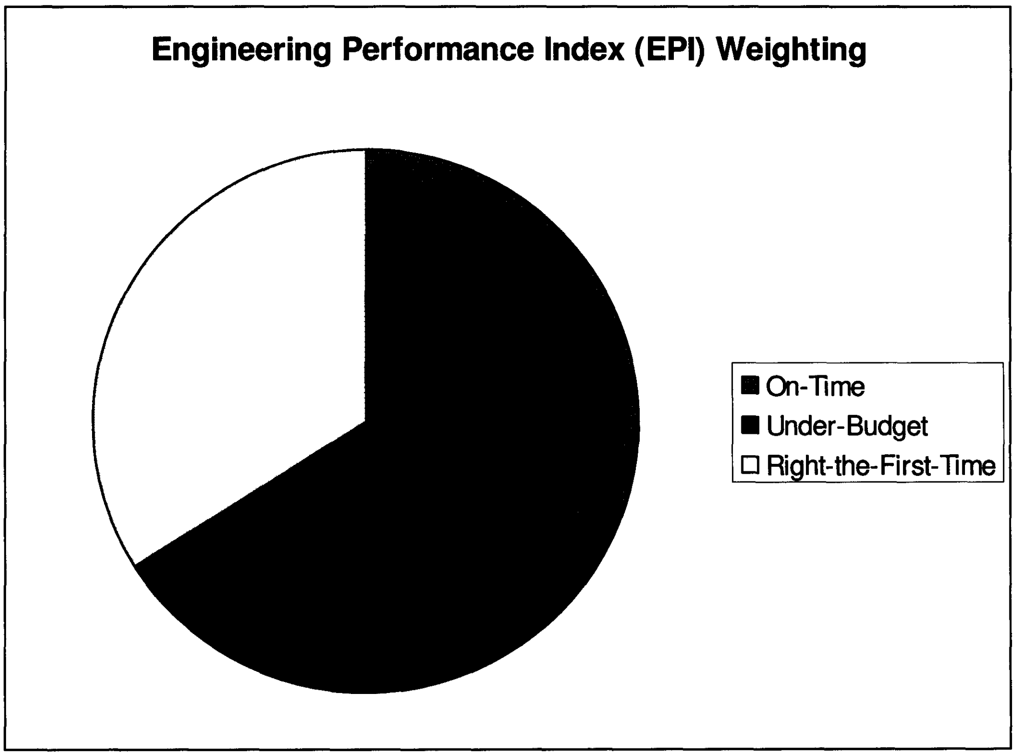


Figure 60. Weighting of On-Time, Under-Budget, and Right-the-First-Time on EPI

Once again, the effects of various factors were modeled through the use of Look-Up table functions. Figures 61-67 below depict the specific table functions that were used in the model. These factors were developed based on personal experience and validated (qualitatively) through the follow up interview process.

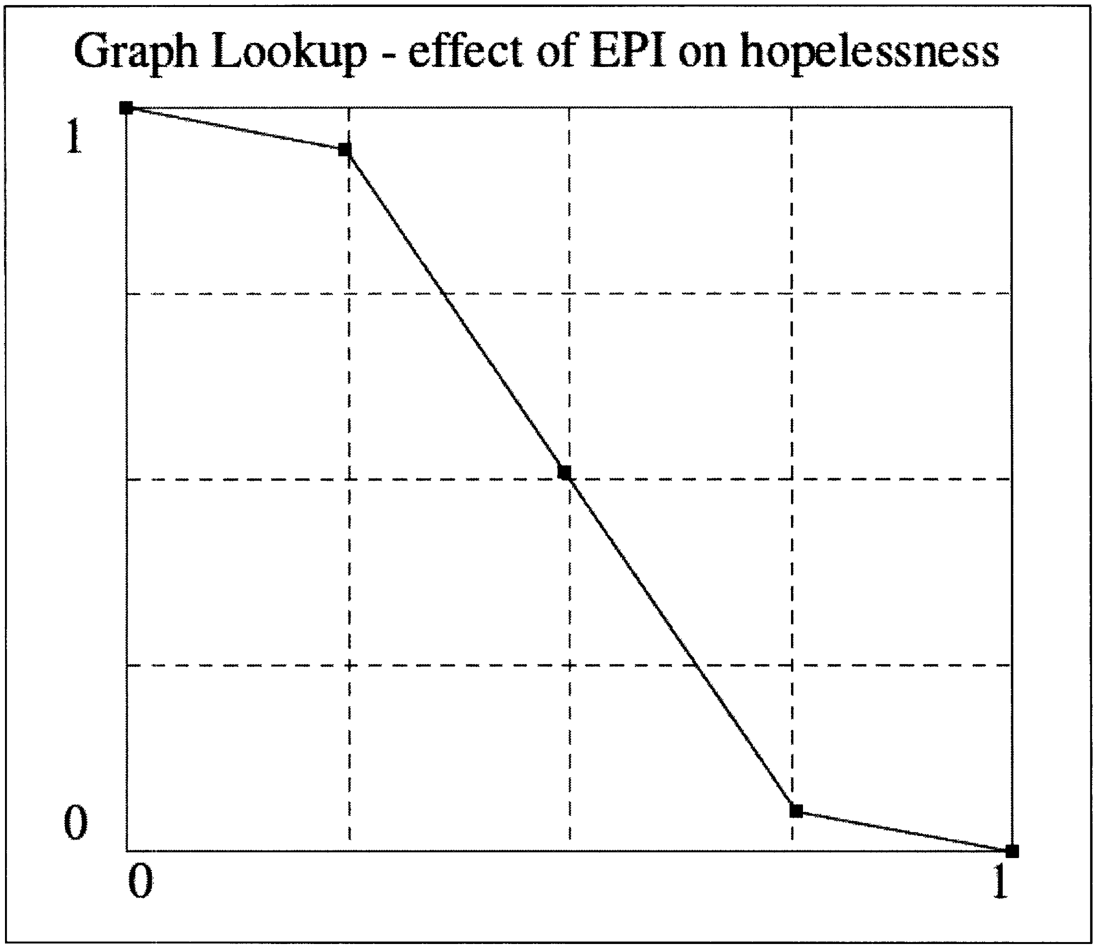


Figure 61. Effect of EPI on EHI

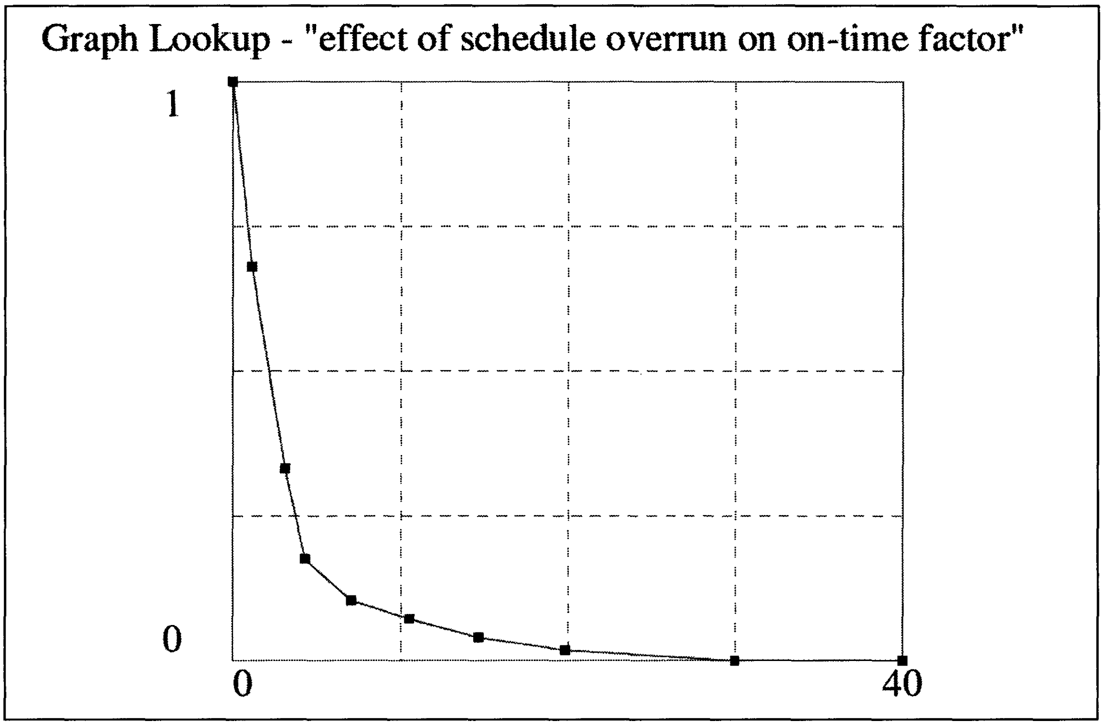


Figure 62. Effect of Schedule Overrun on On-time Factor

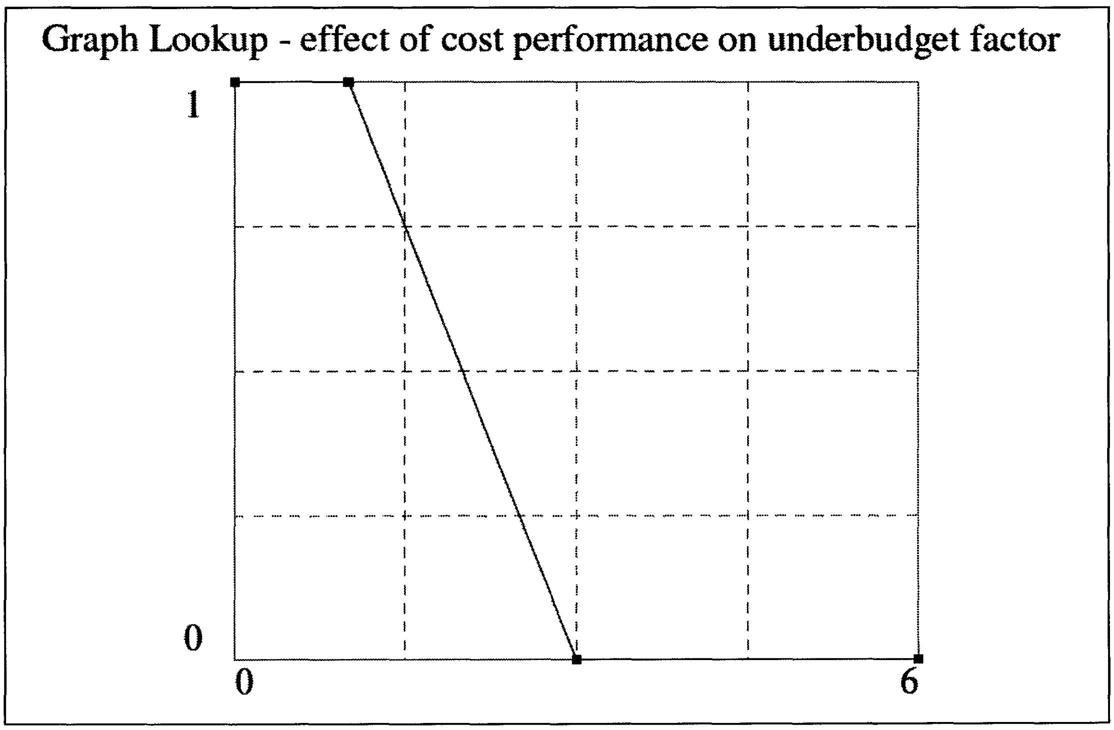


Figure 63. Effect of Cost Performance on Under-Budget Factor

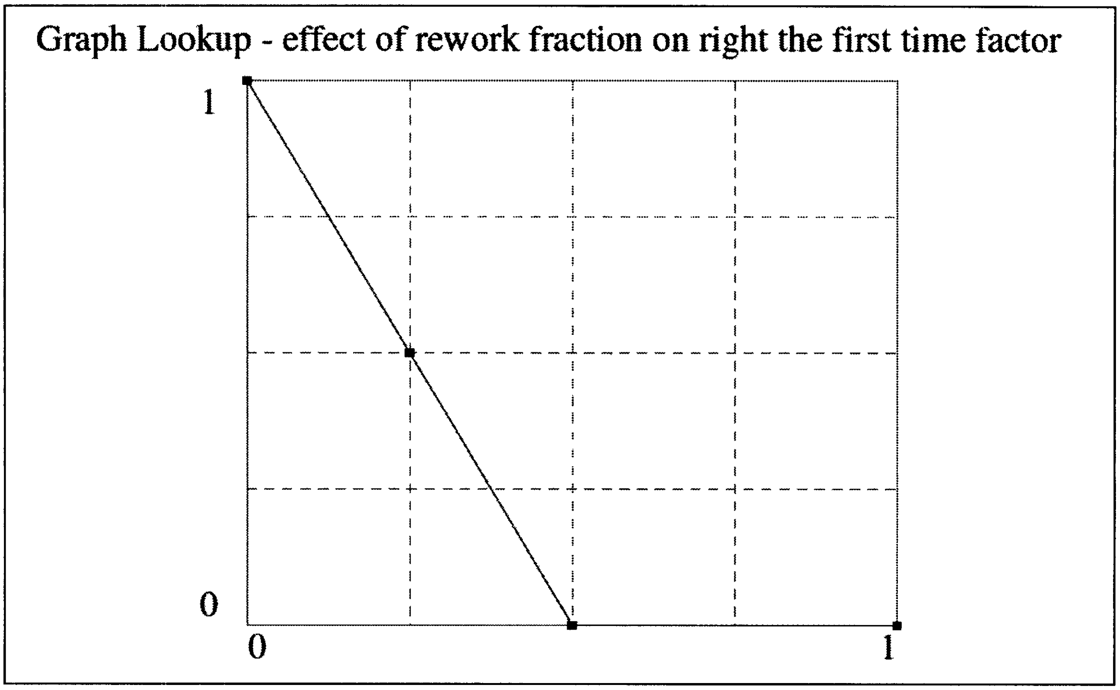


Figure 64. Effect of Rework Fraction on Right-the-First-Time Factor

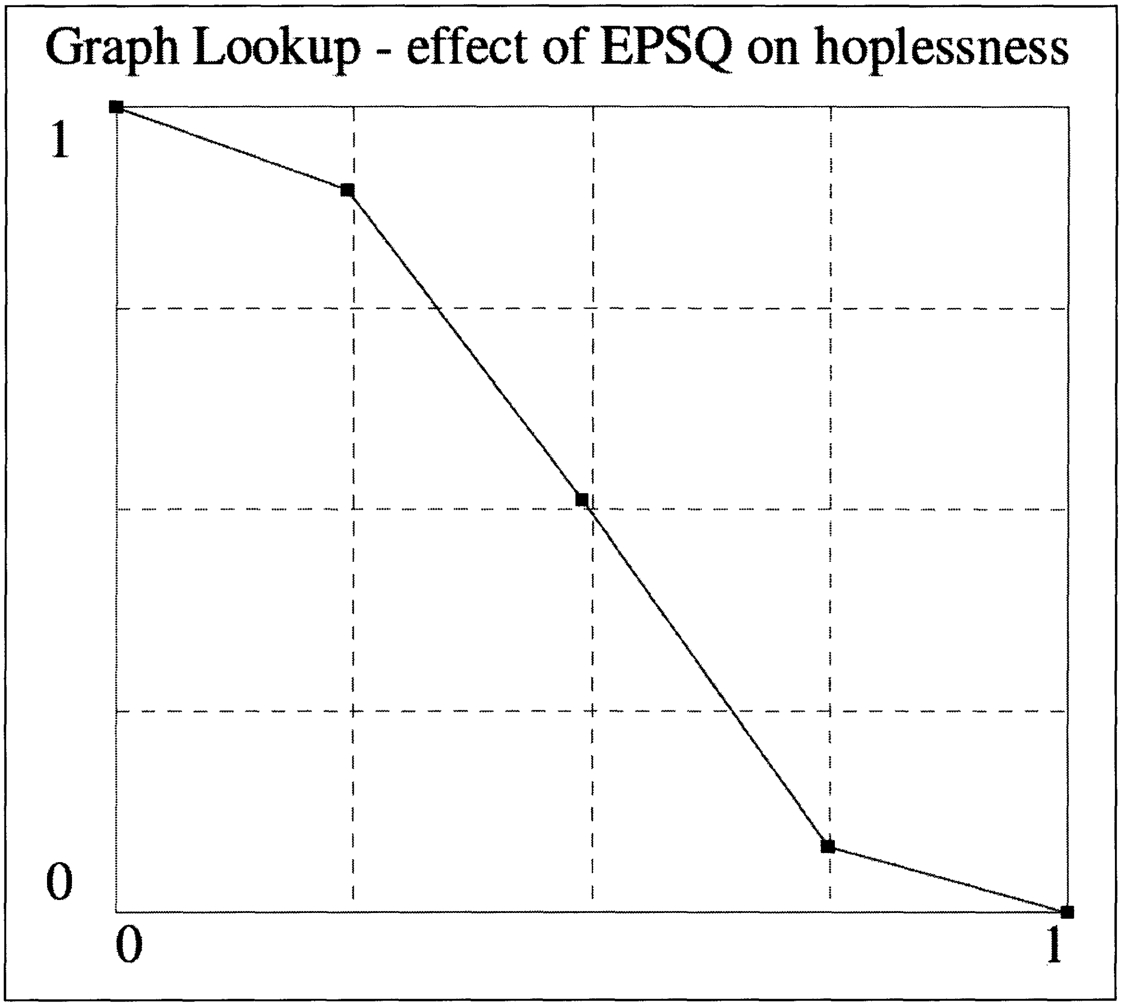


Figure 65. Effect of EPSQ on EHI

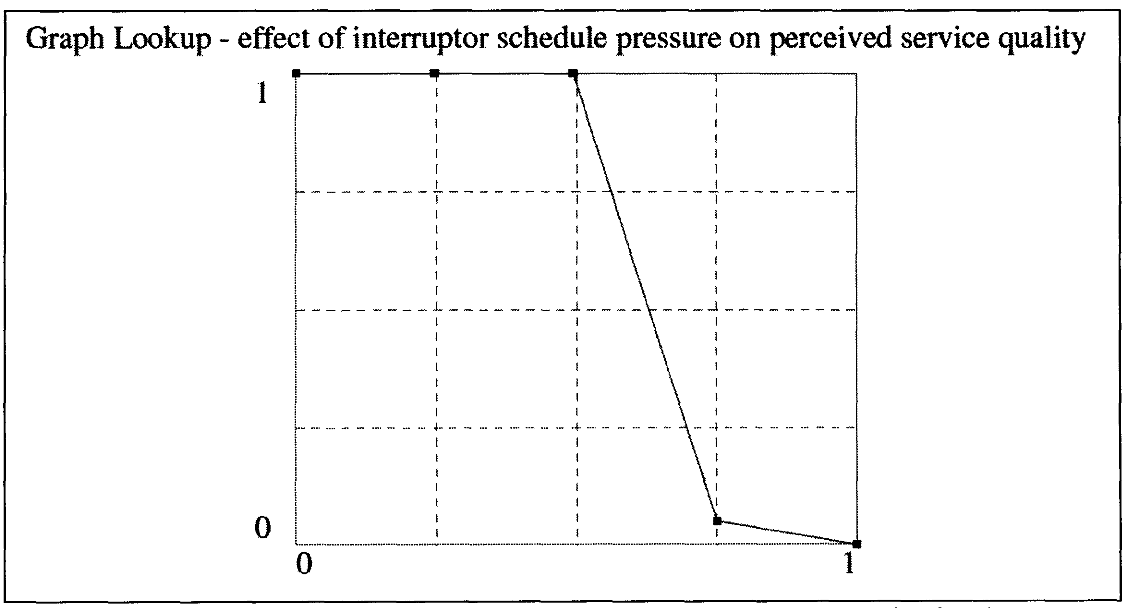


Figure 66. Effect of Interrupter Schedule Pressure on Perceived Service Quality

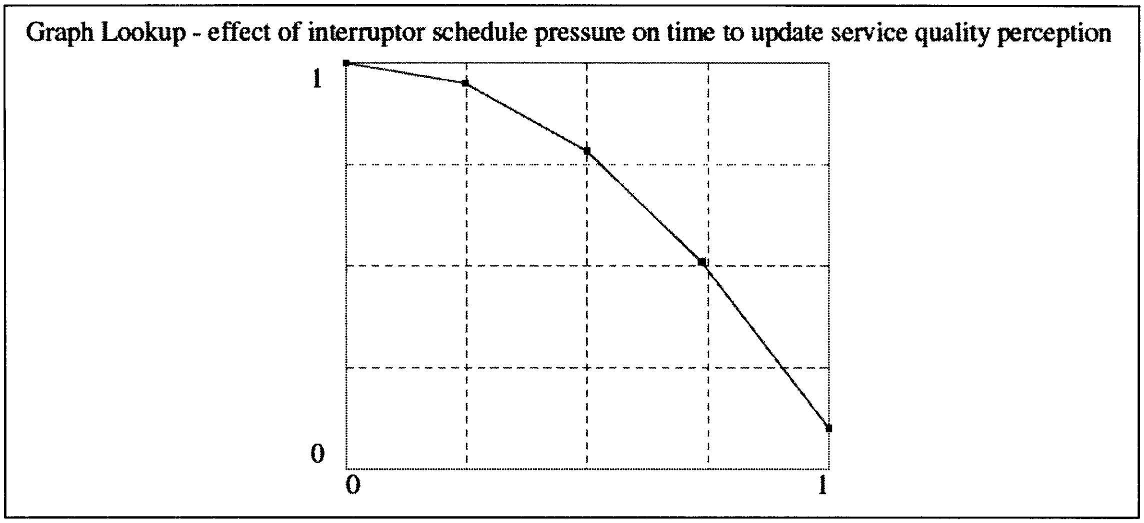


Figure 67. Effect of Interrupter Schedule Pressure on Time to Update Service Quality Perception

All of the components were formulated in the Vensim© PLE modeling and simulation environment. Simulations were carried out for various scenarios. The results of the simulations are provided in the sub-section that follows.

5.3.4 Simulation Results

This sub-section provides the results of the simulations carried out using the formal system dynamics model described above. Simulations were carried out for three "scenarios". The scenarios and their descriptions are:

Perfect World – In this scenario, quality is assumed to be perfect and there are no impacts to productivity as a result of interruptions. In this perfect world scenario, actual performance tracks forecasted performance perfectly.

Semi-Perfect World – In this scenario, quality is assumed to be very high, but not perfect, and there are no impacts to productivity as a result of interruptions.

In this scenario, actual performance tracks forecasted performance closely, but not exactly.

Real World – In this scenario, quality is assumed to be very high nominally, but not perfect, and interruptions are allowed to impact productivity. In this scenario, the actual performance deviates significantly from forecasted performance.

The results of each scenario are presented in the sub-sections that follow.

In addition, a sensitivity analysis was performed looking at the effect of schedule pressure on the system behavior. In this analysis, the effect of schedule pressure on the willingness to accept interruptions was "dialed-up" by 175% and "dialed-down" by 50% to examine the effects of changes in response policy on system behavior. The results of these simulations are provided in the last subsection.

5.3.4.1 In a Perfect World: No Interruptions, Perfect Quality

The following factors are plotted, over time, for simulations of the perfect world scenario:

- **Actual Cash vs. Forecast Cash**
- **Actual Profit vs. Forecast Profit**
- **Actual % Task Complete vs. Budgeted % Task Complete vs. Perceived % Task Complete**
- **Anticipated Schedule Overrun**
- **Willingness to Accept Interruptions**
- **On-Time vs. Under-Budget vs. Right-the-First-Time**

- **EPI**
- **EPSQ**
- **EHI**

These output plots are provided in Figures 68-76 below.

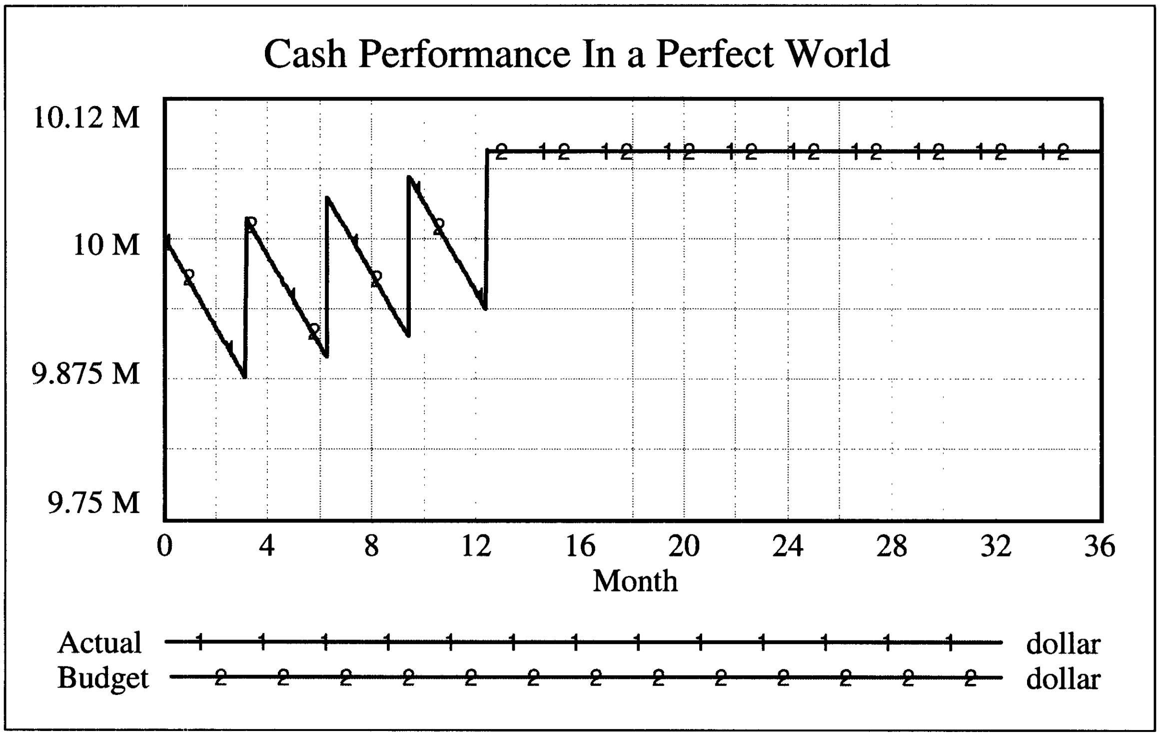


Figure 68. Cash in a Perfect World

In a perfect world, actuals track budgets precisely. There are no impacts to productivity or quality from any factors.

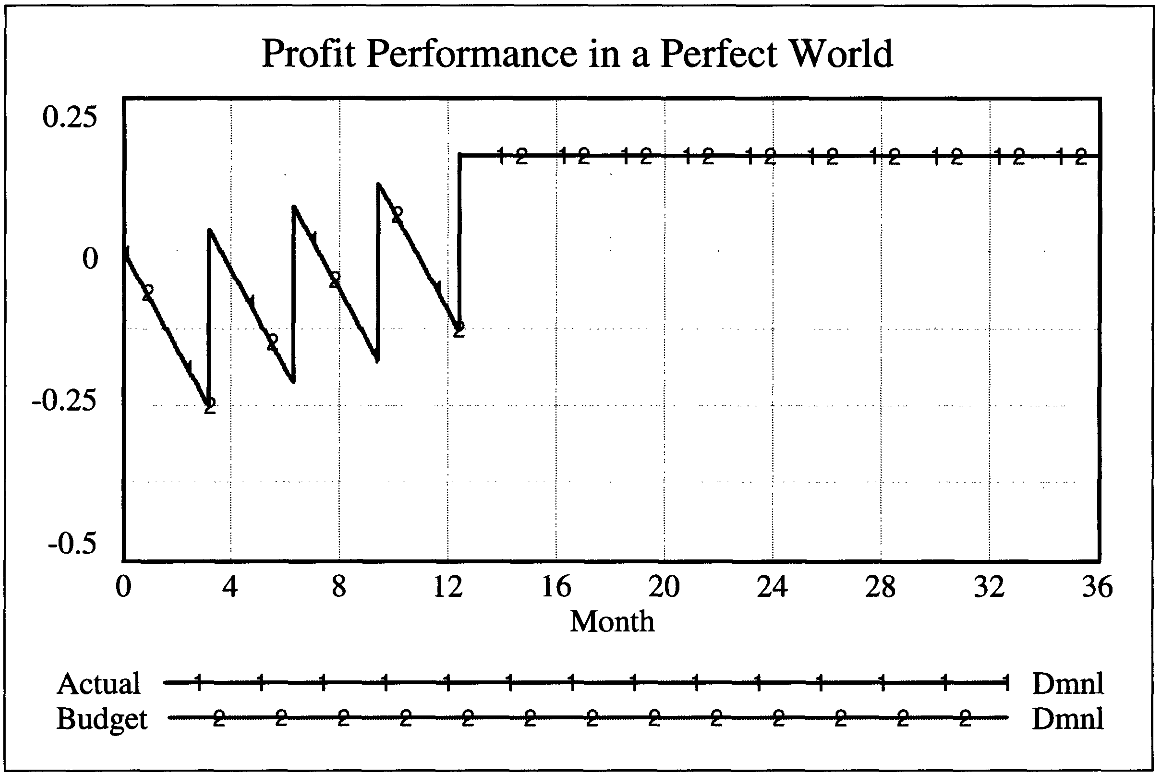


Figure 69. Profit in a Perfect World

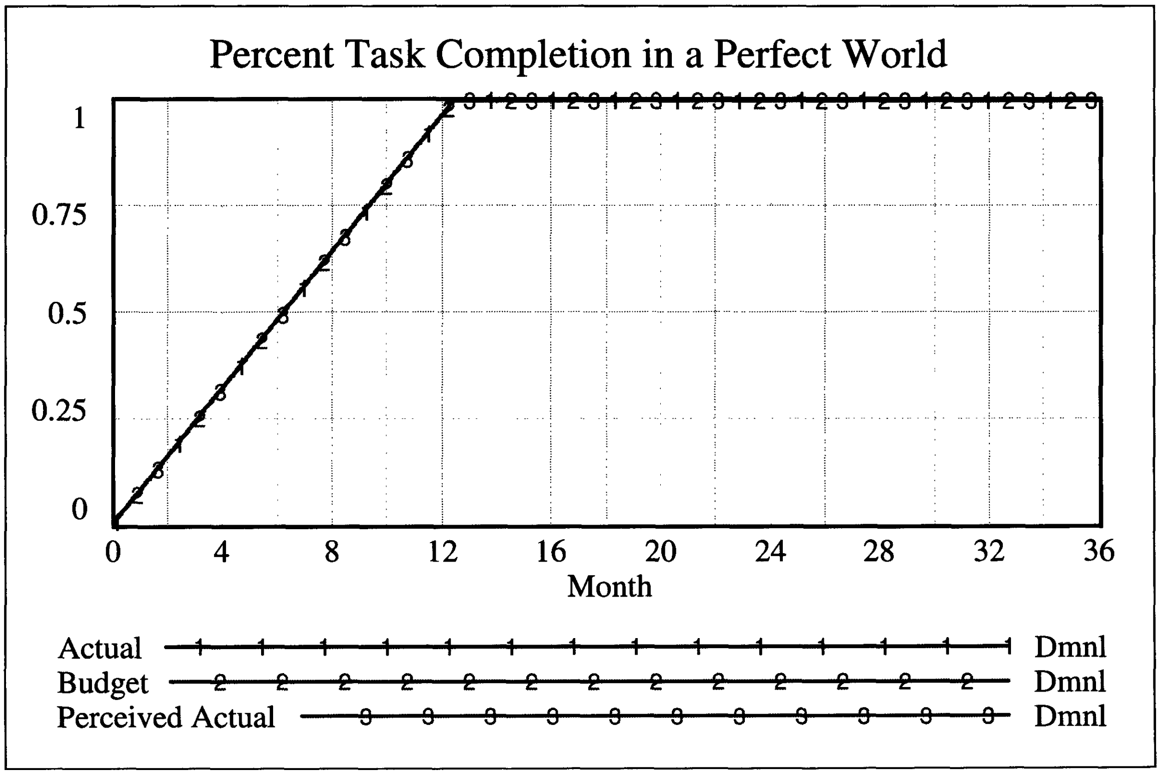


Figure 70. Task Completion % in a Perfect World

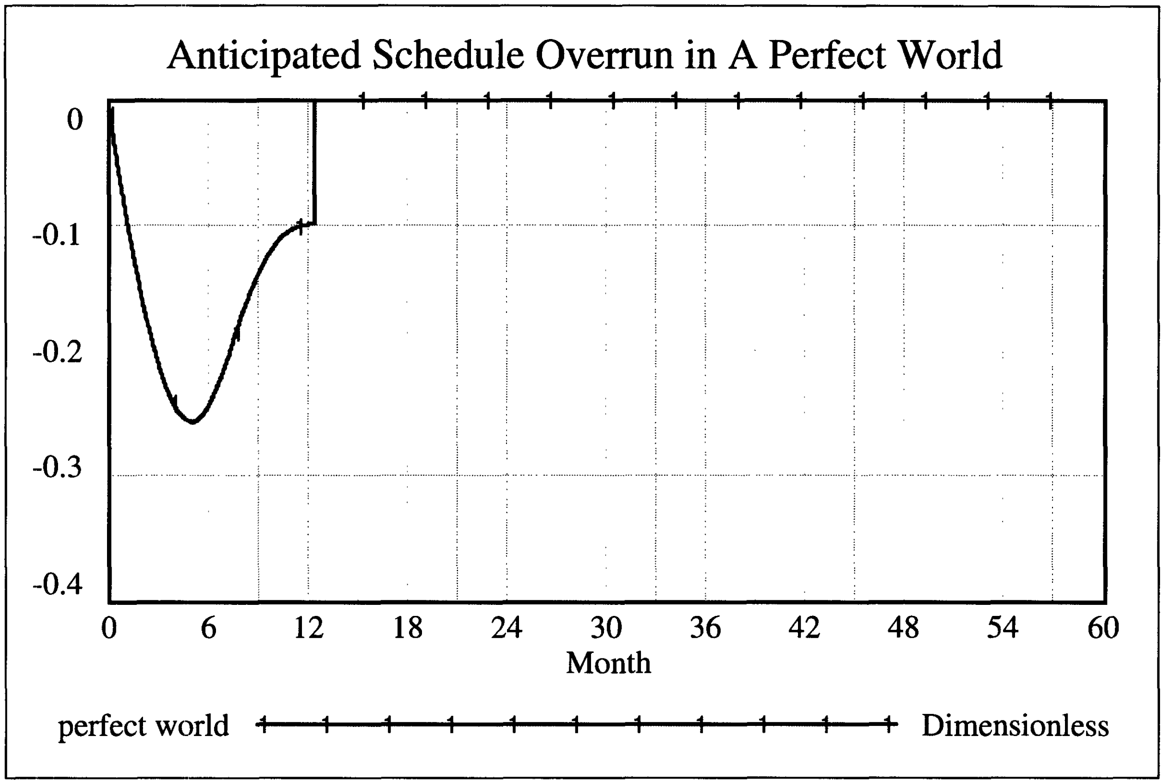


Figure 71. Anticipated Schedule Overrun in A Perfect World

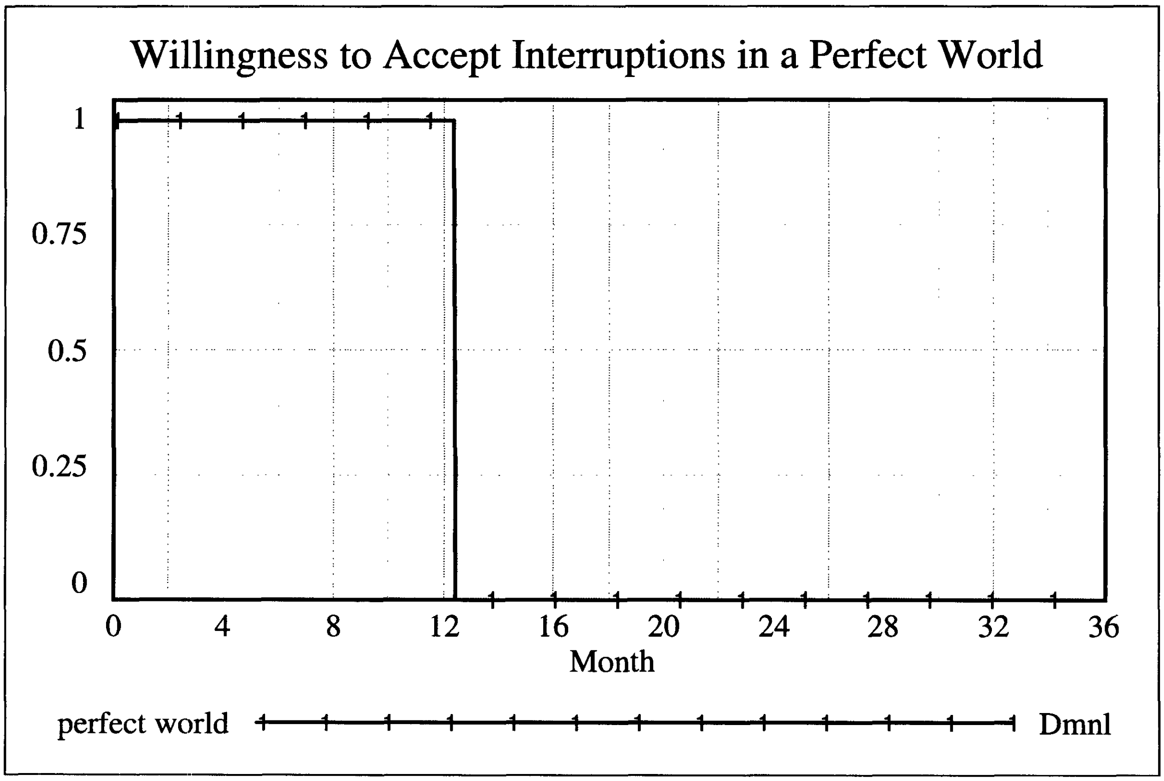


Figure 72. Willingness to Accept Interruptions ina Perfect World

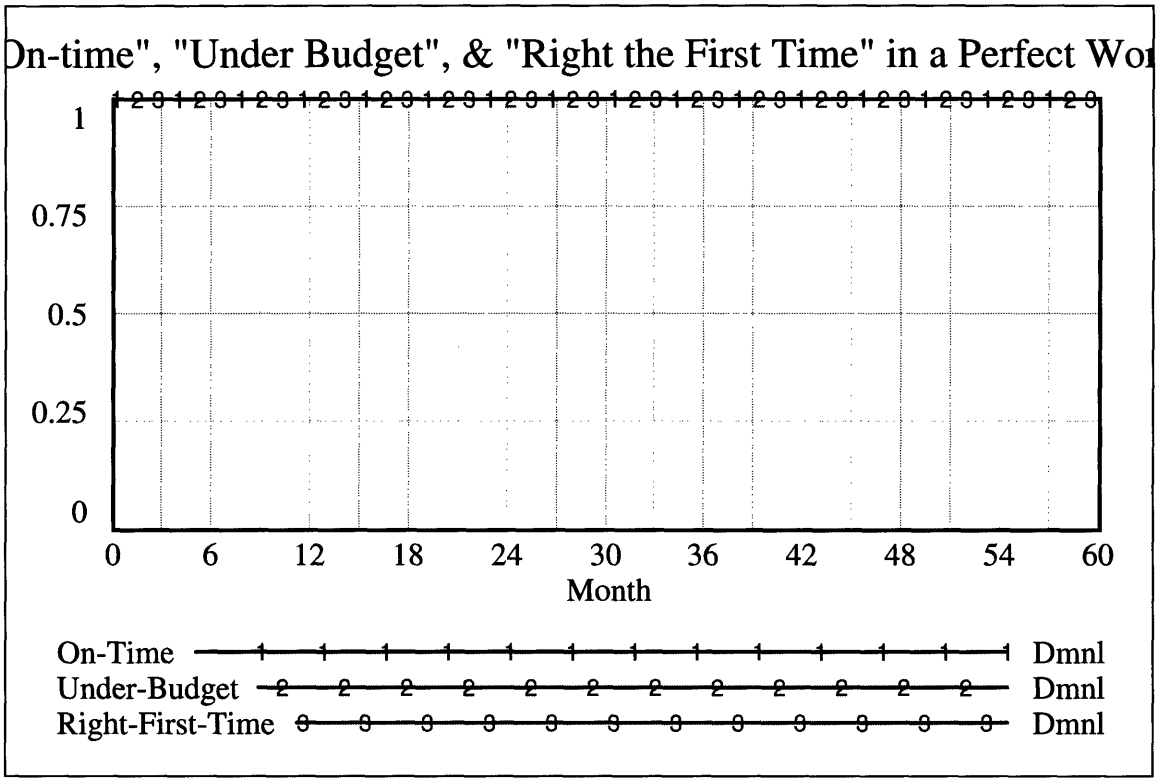


Figure 73. On-Time, Under-Budget, Right-the-First-Time in a Perfect World

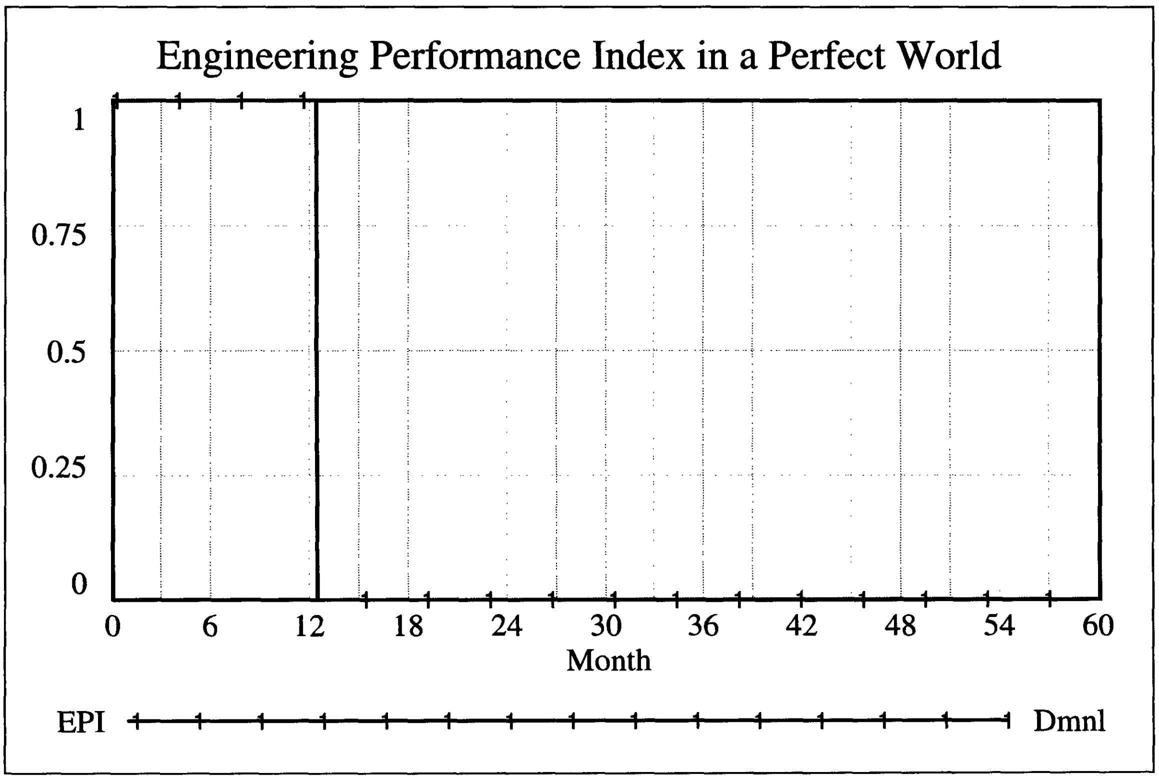


Figure 74. EPI in a Perfect World

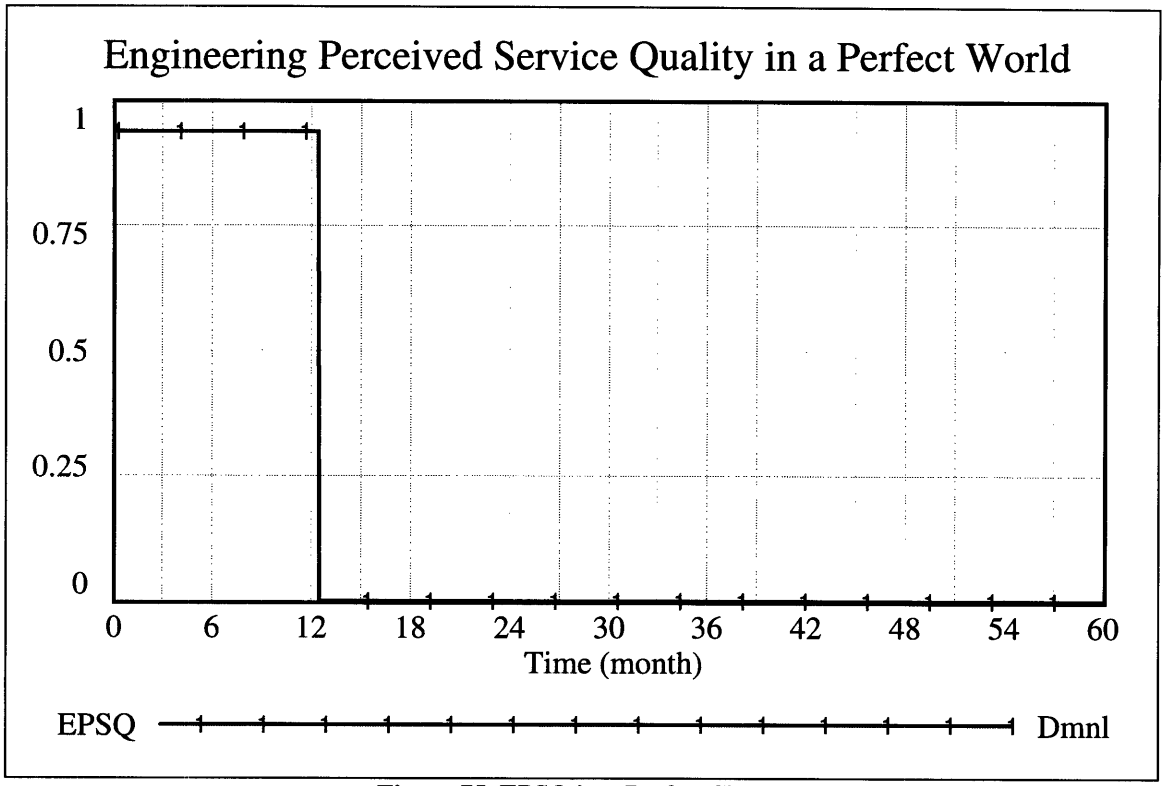


Figure 75. EPSQ in a Perfect World

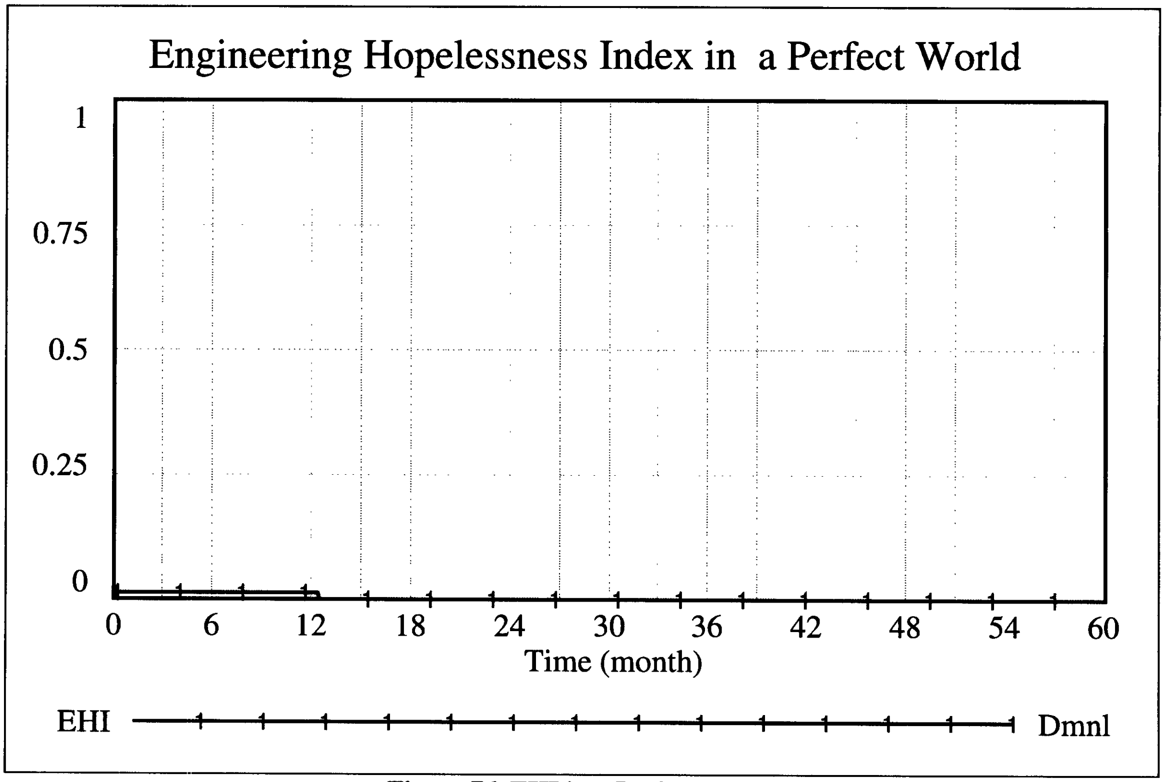


Figure 76. EHI in a Perfect World

All plotted measures of project performance indicate that everything is according to plan while the indices of engineering performance are also very good.

5.3.4.2 In a Semi-Perfect World: No Interruptions, but Imperfect Quality

The following factors are plotted, over time, for simulations of the semi-perfect world scenario:

- **Actual Cash vs. Forecast Cash**
- **Actual Profit vs. Forecast Profit**
- **Actual % Task Complete vs. Budgeted % Task Complete vs. Perceived % Task Complete**
- **Anticipated Schedule Overrun**
- **Willingness to Accept Interruptions**
- **On-Time vs. Under-Budget vs. Right-the-First-Time**
- **EPI**
- **EPSQ**
- **EHI**

These output plots are provided in Figures 77-85 below. In a semi-perfect world, quality is not perfect (i.e. less than 1, or 100%). As a result rework is generated which leads to actual performance lagging forecast.

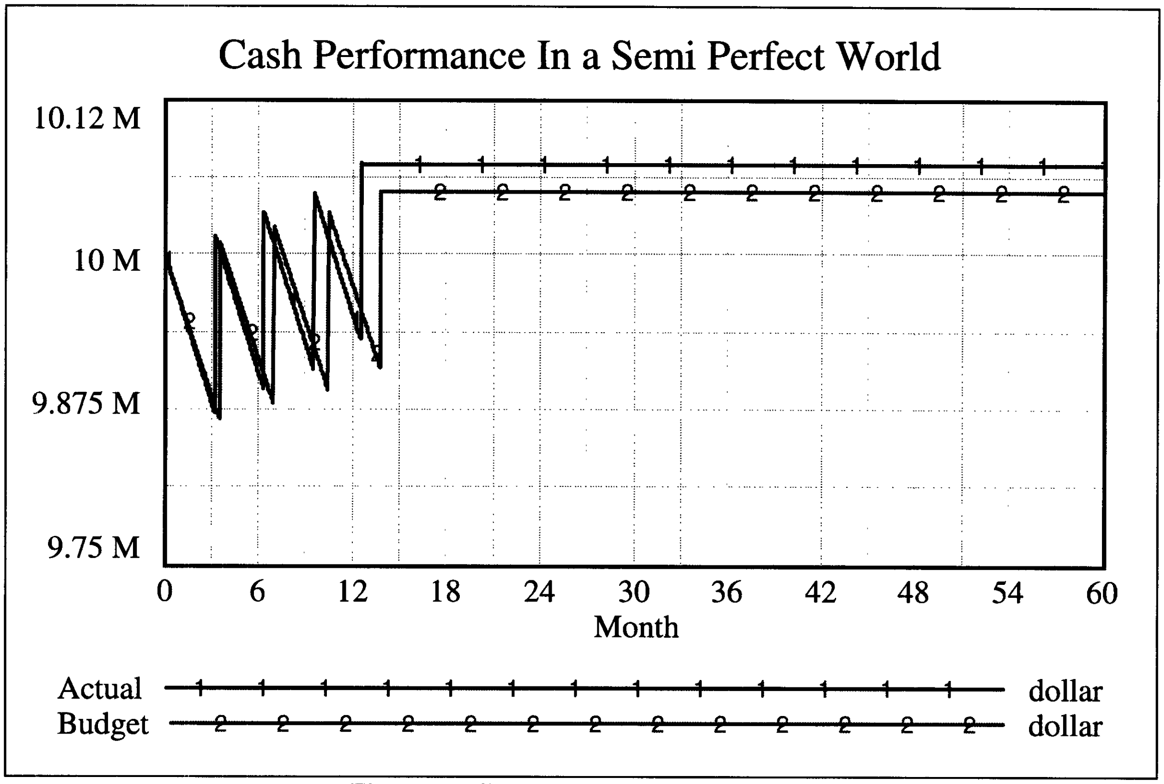


Figure 77. Cash in a Semi-Perfect World

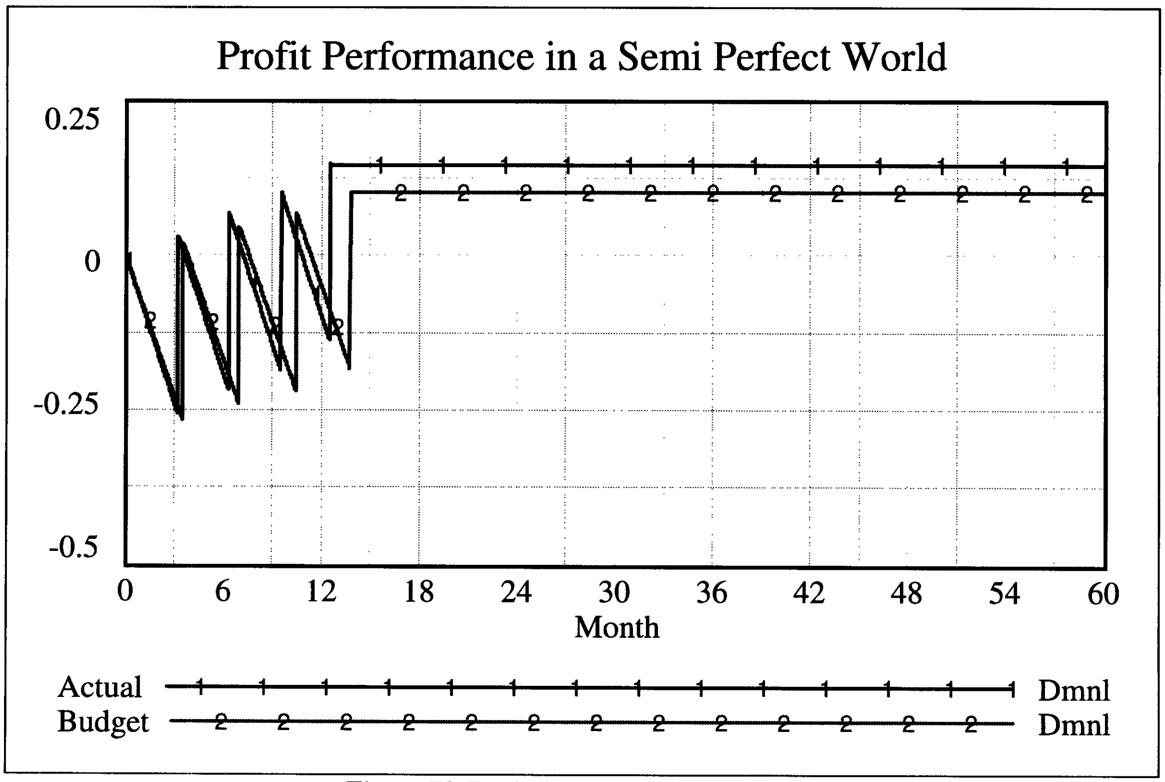


Figure 78. Profit in a Semi-Perfect World

Cash and profit are both effected adversely as a result of imperfect quality and the resulting rework generation. Ultimately the project takes longer to complete with delayed milestone payments. Overall profit margin, although still greater than zero (in these simulations) is reduced from the forecast(target) value.

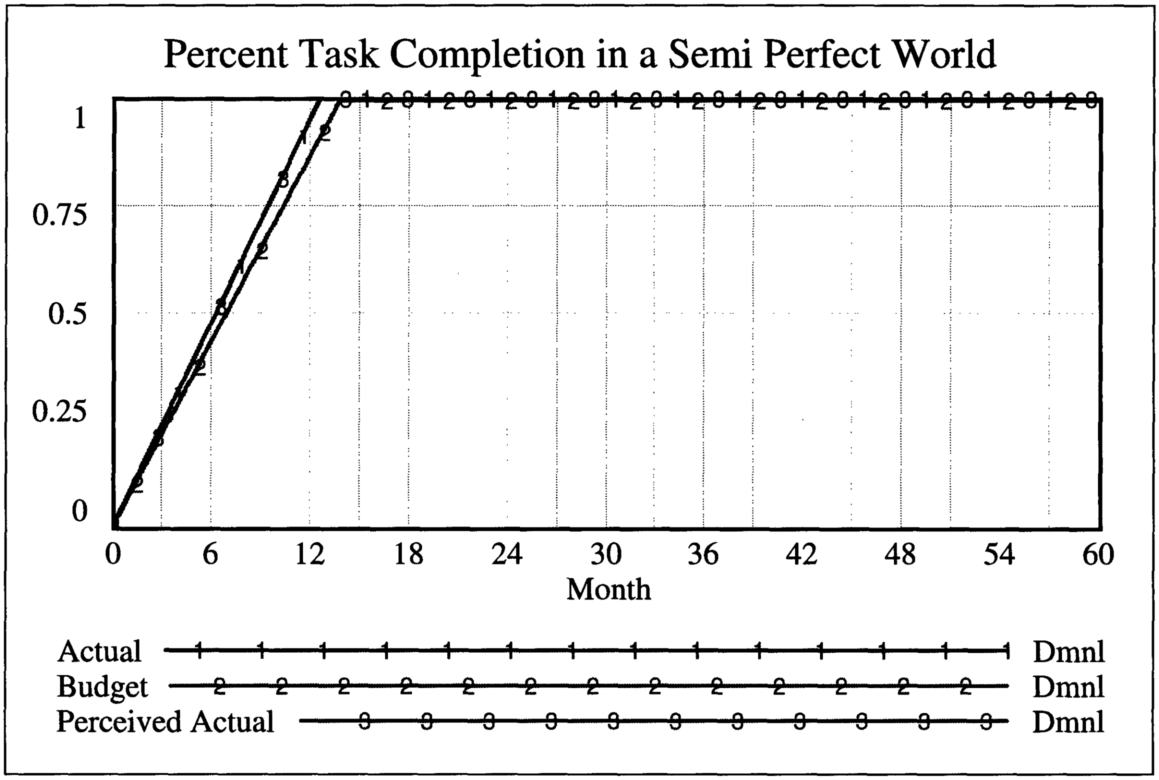


Figure 79. Task Completion % in a Semi-Perfect World

Again, because there are no impacts to productivity from interruptions, the measures of engineering performance are still very good although not as good as the perfect world scenario.

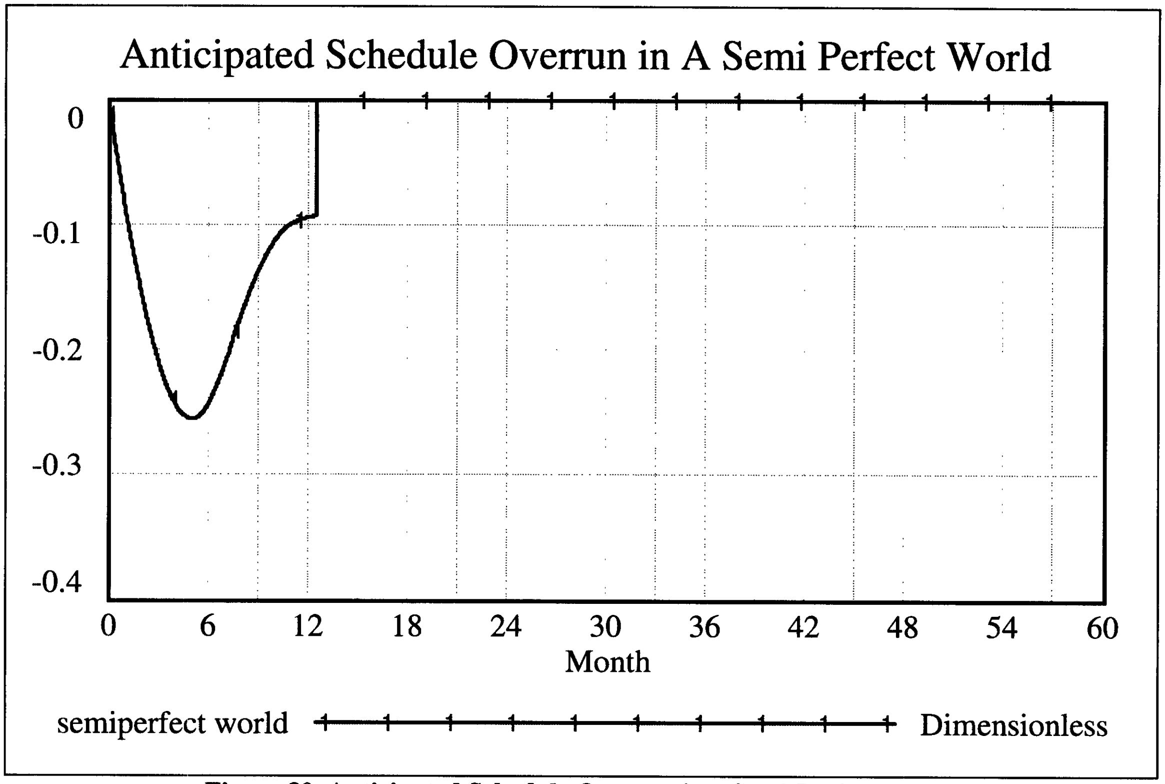


Figure 80. Anticipated Schedule Overrun in a Semi-Perfect World

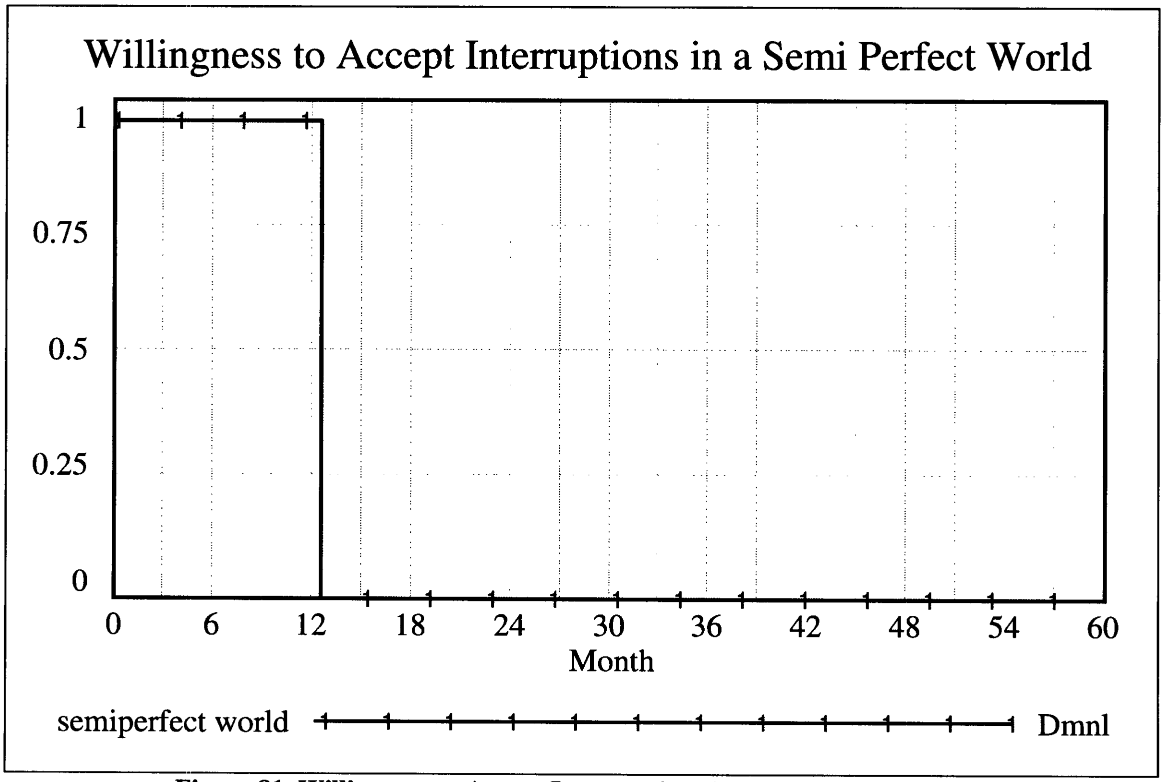


Figure 81. Willingness to Accept Interruptions in a Semi-Perfect World

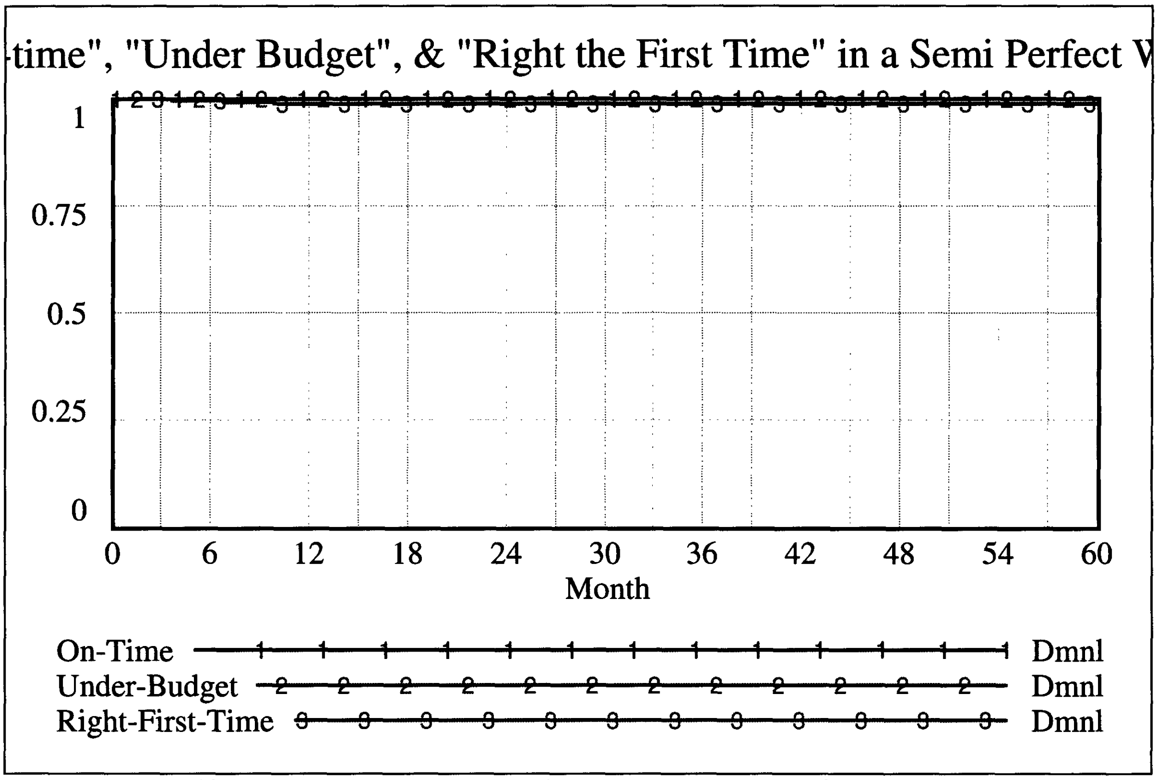


Figure 82. On-Time, Under-Budget, Right-the-First-Time in a Semi-Perfect World

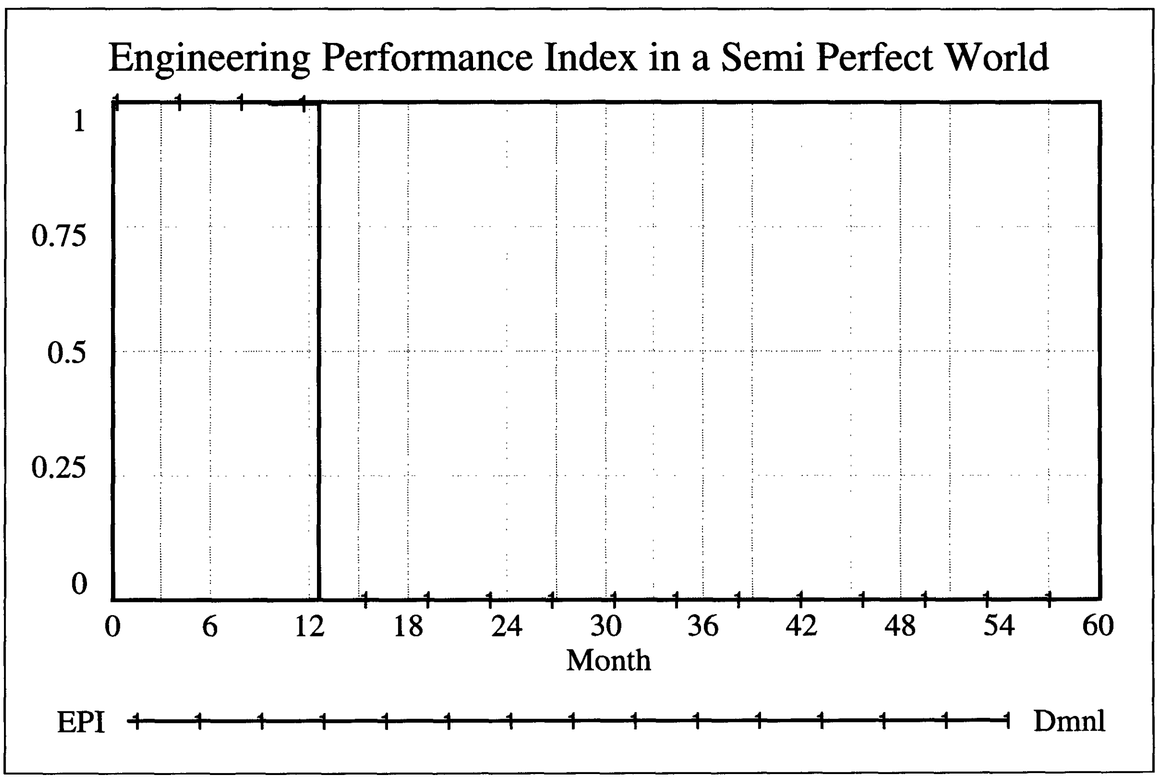


Figure 83. EPI in a Semi-Perfect World

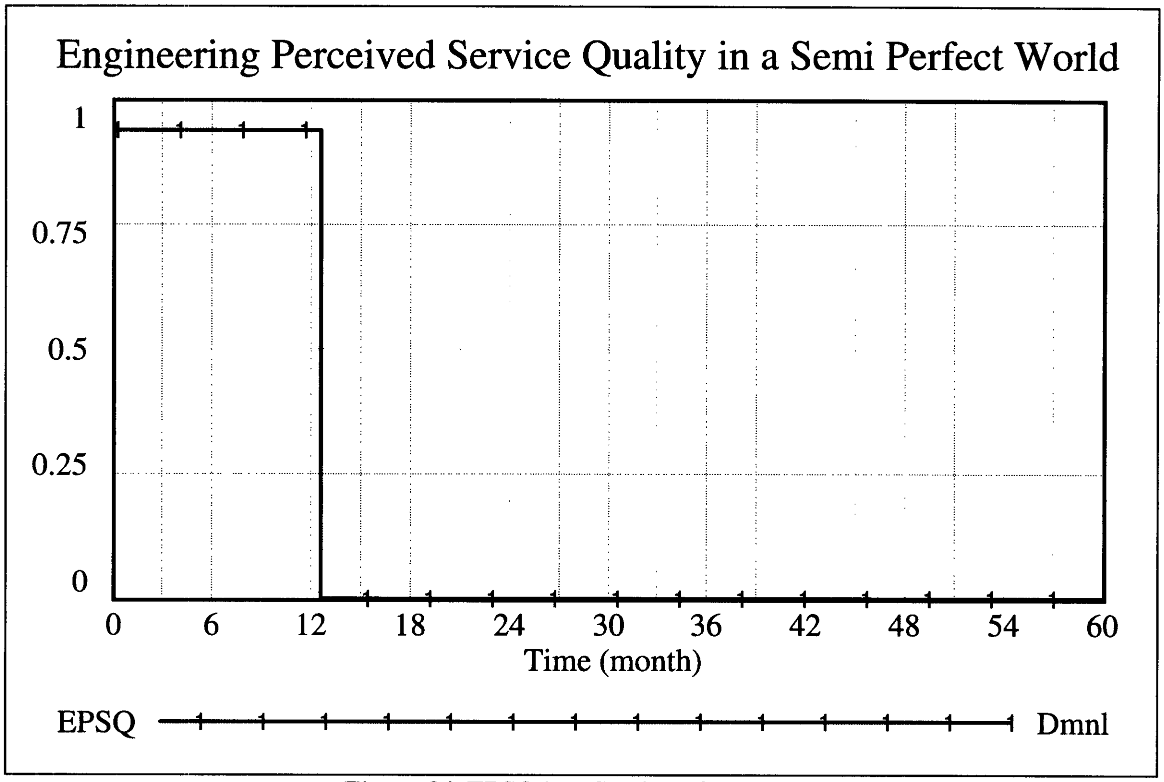


Figure 84. EPSQ in a Semi-Perfect World

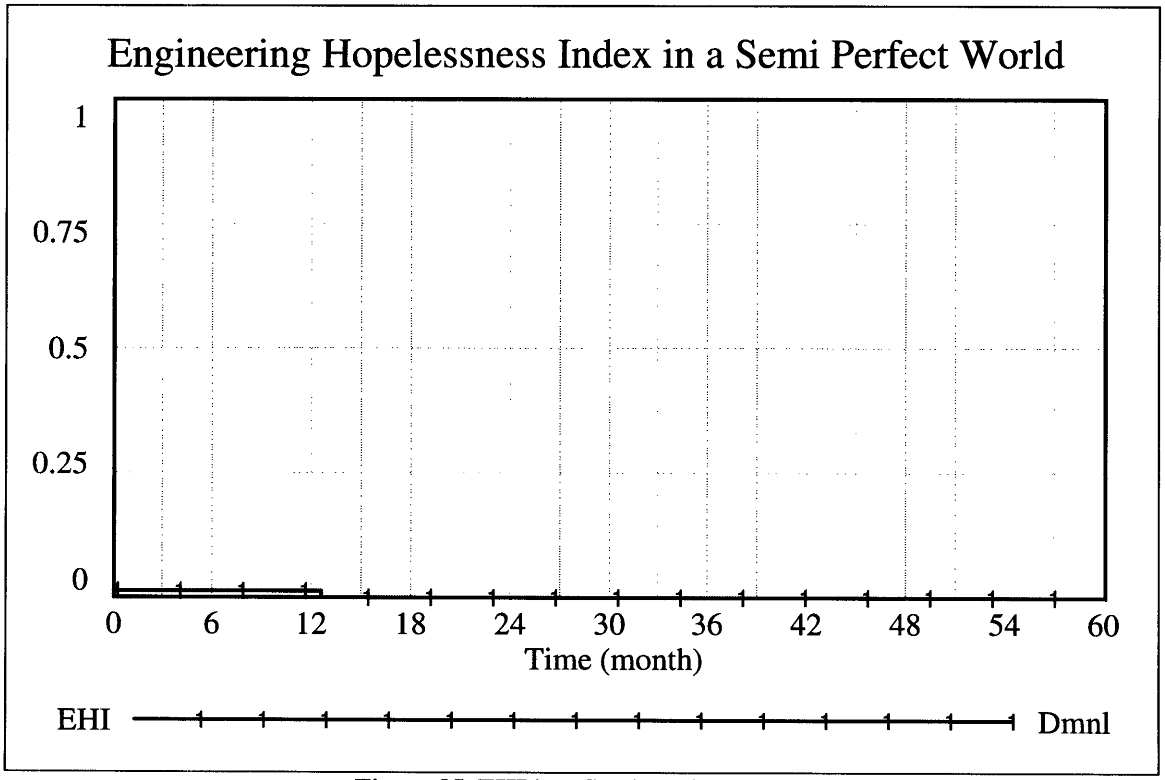


Figure 85. EHI in a Semi-Perfect World

The semi-perfect world scenario can be considered a baseline from which to compare the system performance and behavior with and without interruptions.

5.3.4.3 In the Real World: Interruptions and Imperfect Quality

The following factors are plotted, over time, for simulations of the real world scenario:

- **Actual Cash vs. Forecast Cash**
- **Actual Profit vs. Forecast Profit**
- **Actual % Task Complete vs. Budgeted % Task Complete vs. Perceived % Task Complete**
- **Anticipated Schedule Overrun**
- **Willingness to Accept Interruptions**
- **On-Time vs. Under-Budget vs. Right-the-First-Time**
- **EPI**
- **EPSQ**
- **EHI**

These output plots are provided in Figures 86-94 below. In the real world, interruptions play a significant role in the performance of the project task execution process. In the simulations, profit and cash are affected significantly due to very long delays in reaching milestones and much higher costs to complete as a result of productivity impacts.

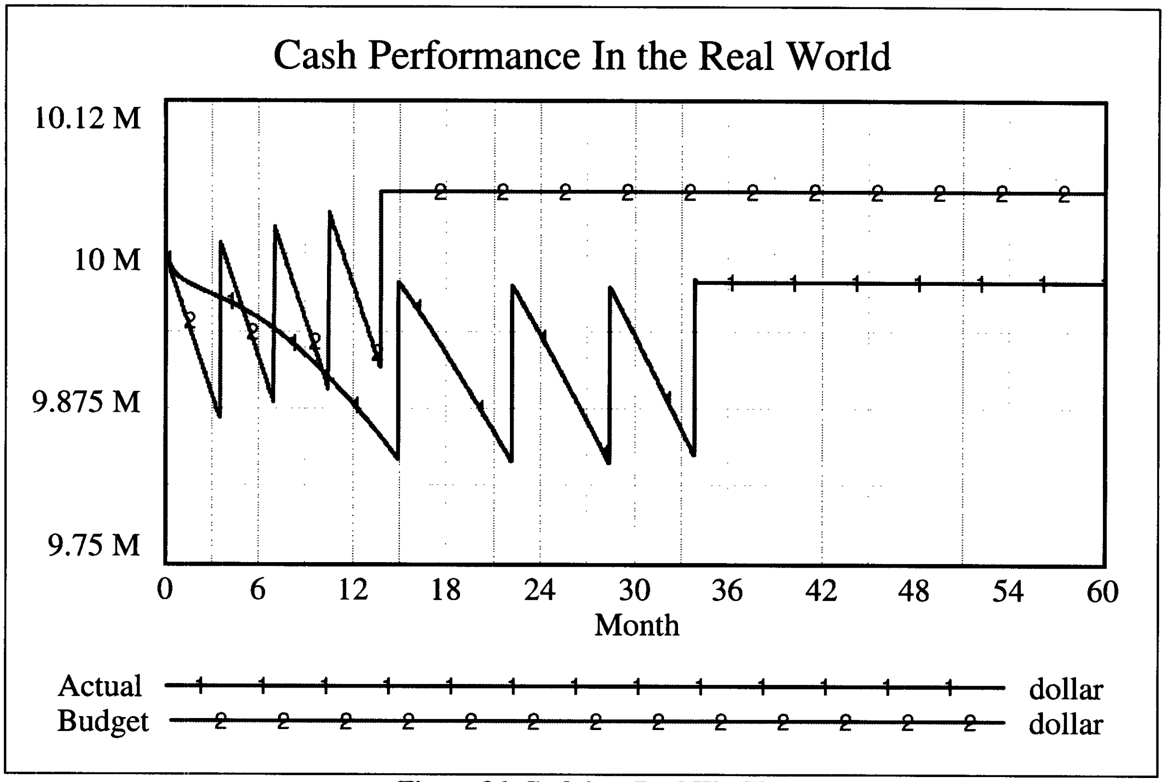


Figure 86. Cash in a Real World

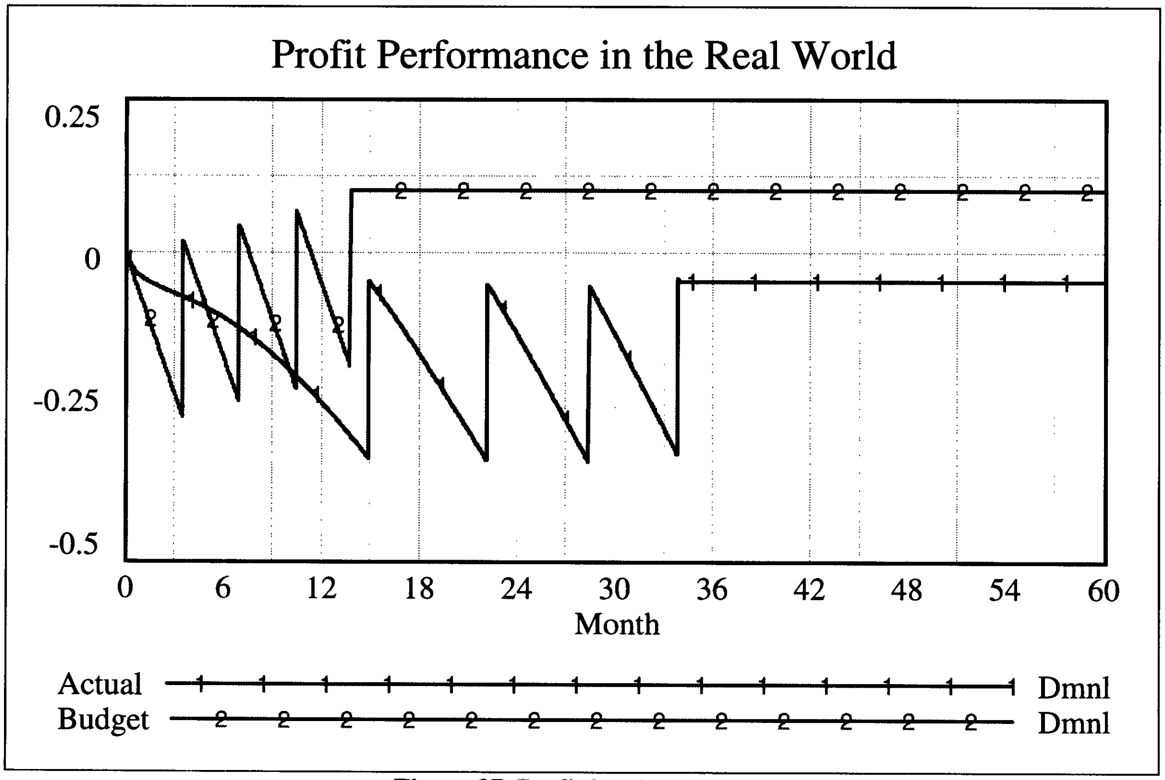


Figure 87. Profit in a Real World

In figures 86 and 87 above, the duration required for completion of the project is roughly doubled, cash is reduced from its original position, and profit margin is negative.

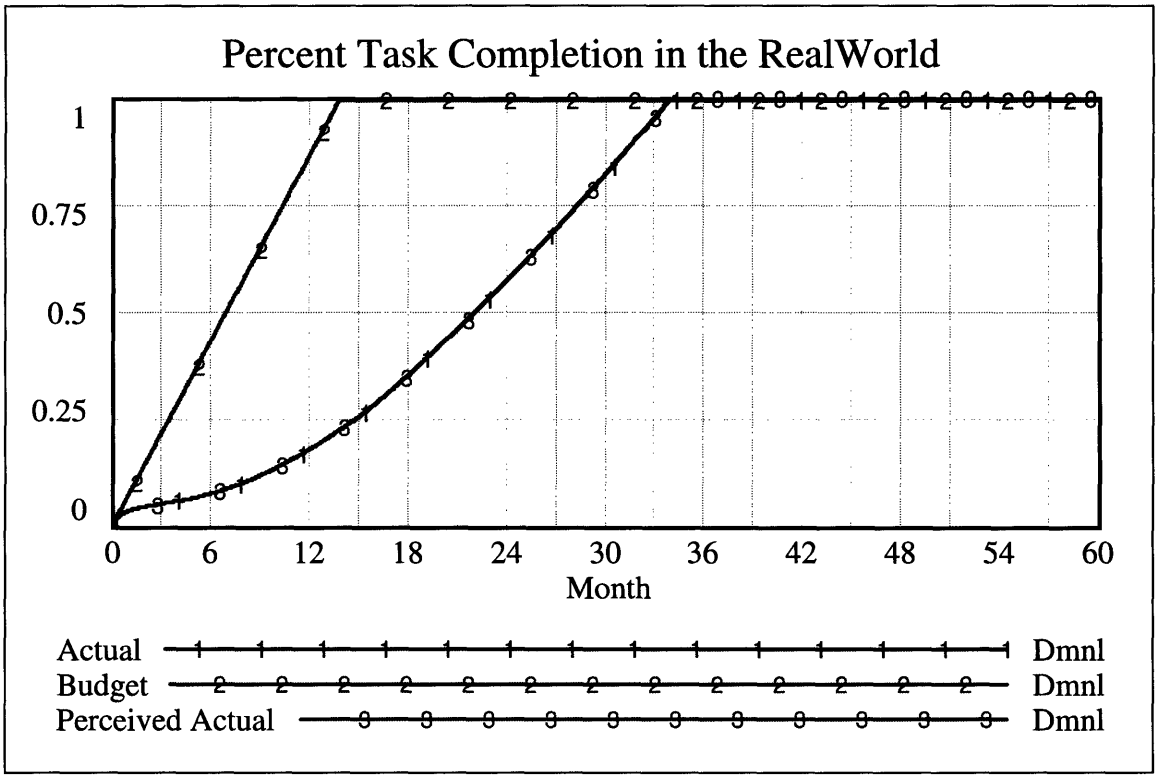


Figure 88. Task Completion % in a Real World

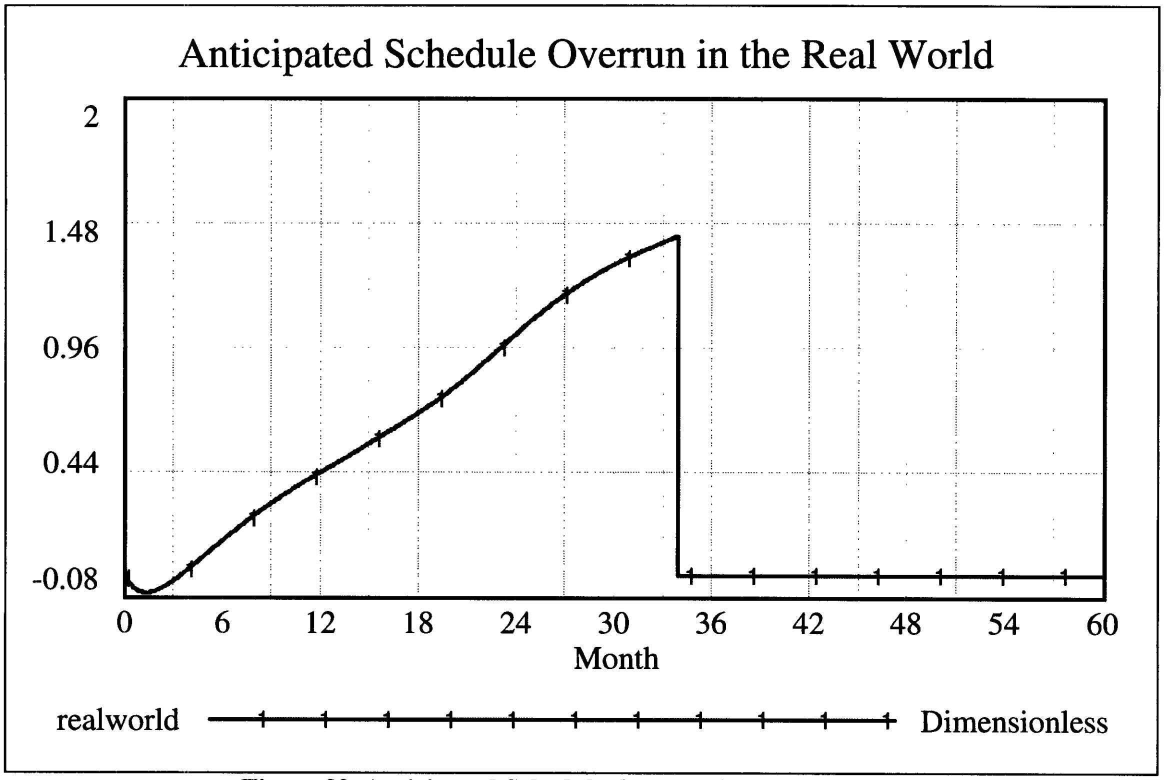


Figure 89. Anticipated Schedule Overrun in the Real World

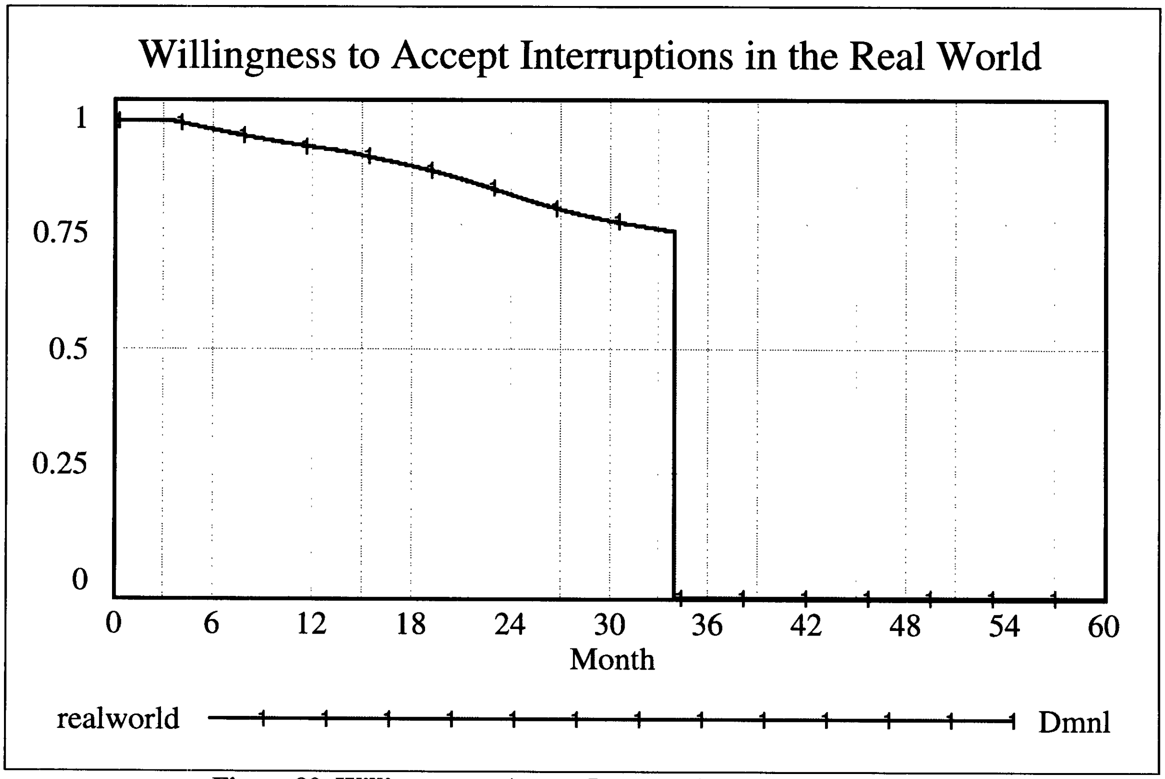


Figure 90. Willingness to Accept Interruptions in the Real World

As seen in Figure 90 above schedule overruns increase schedule pressure significantly leading to a drop in the willingness to accept interruptions. This self-preservation mechanism helps to slow the downward slide of performance.

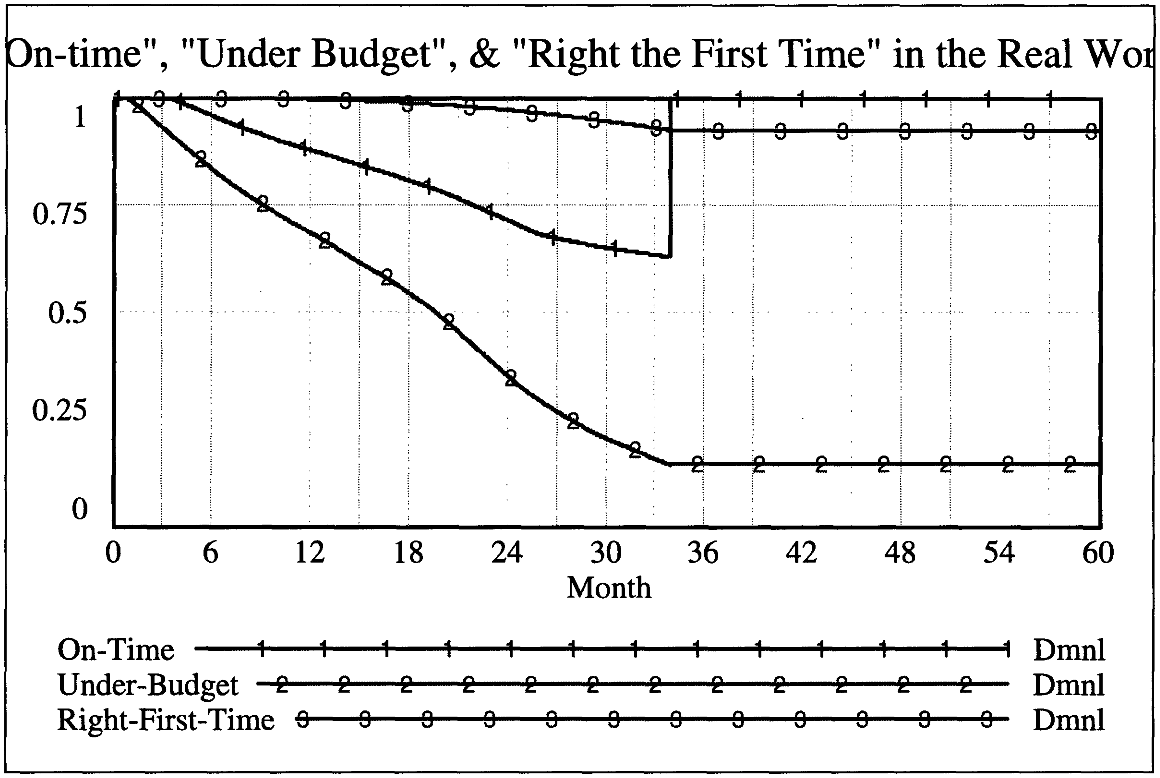


Figure 91. On-Time, Under-Budget, Right-the-First-Time in a Perfect World

The factors that contribute to EPI drop steadily despite the moderating effect of schedule pressure. The most significant impacts are to budget performance, followed by delivery performance, and finally quality. These, of course, map directly to business financial performance, customer satisfaction, and potential warranty issues.

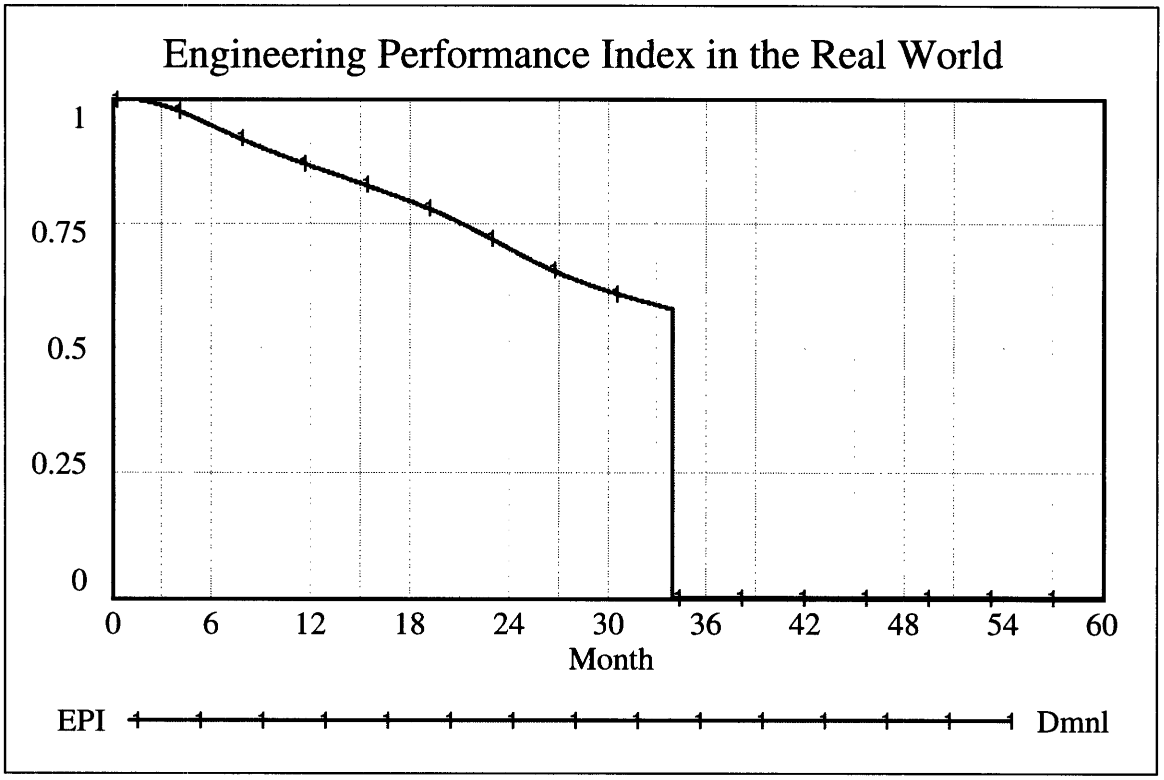


Figure 92. EPI in a Real World

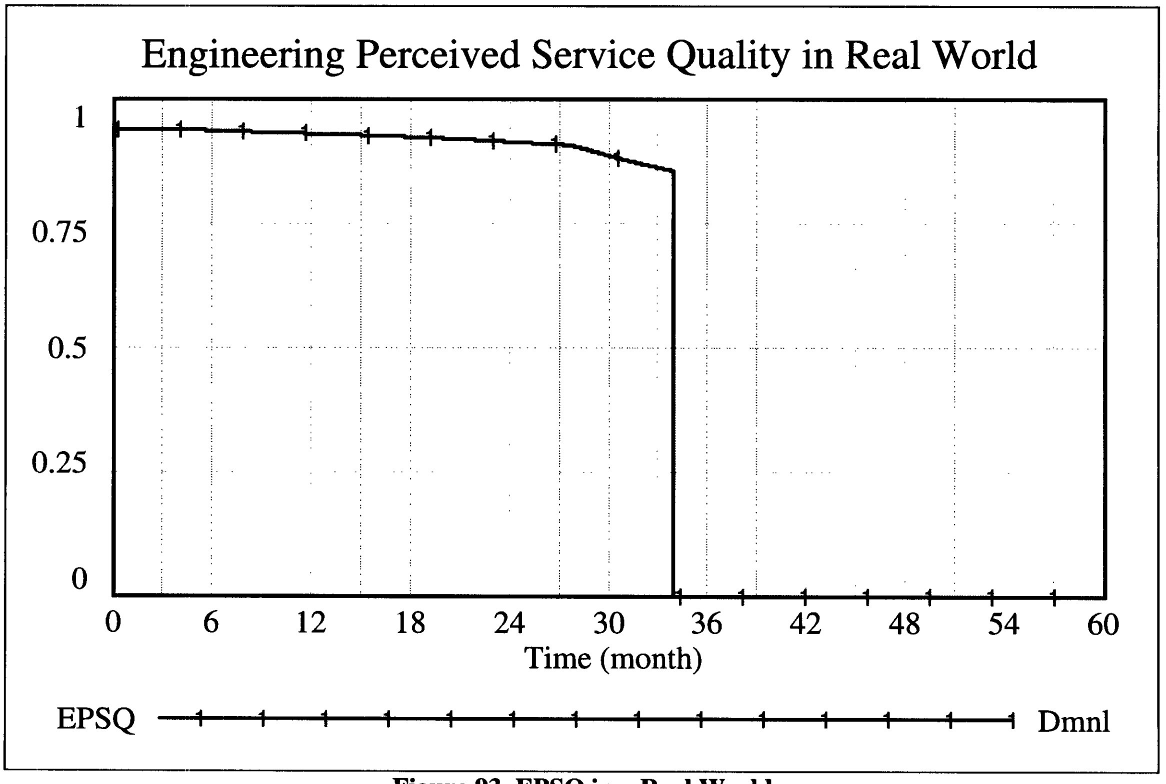


Figure 93. EPSQ in a Real World

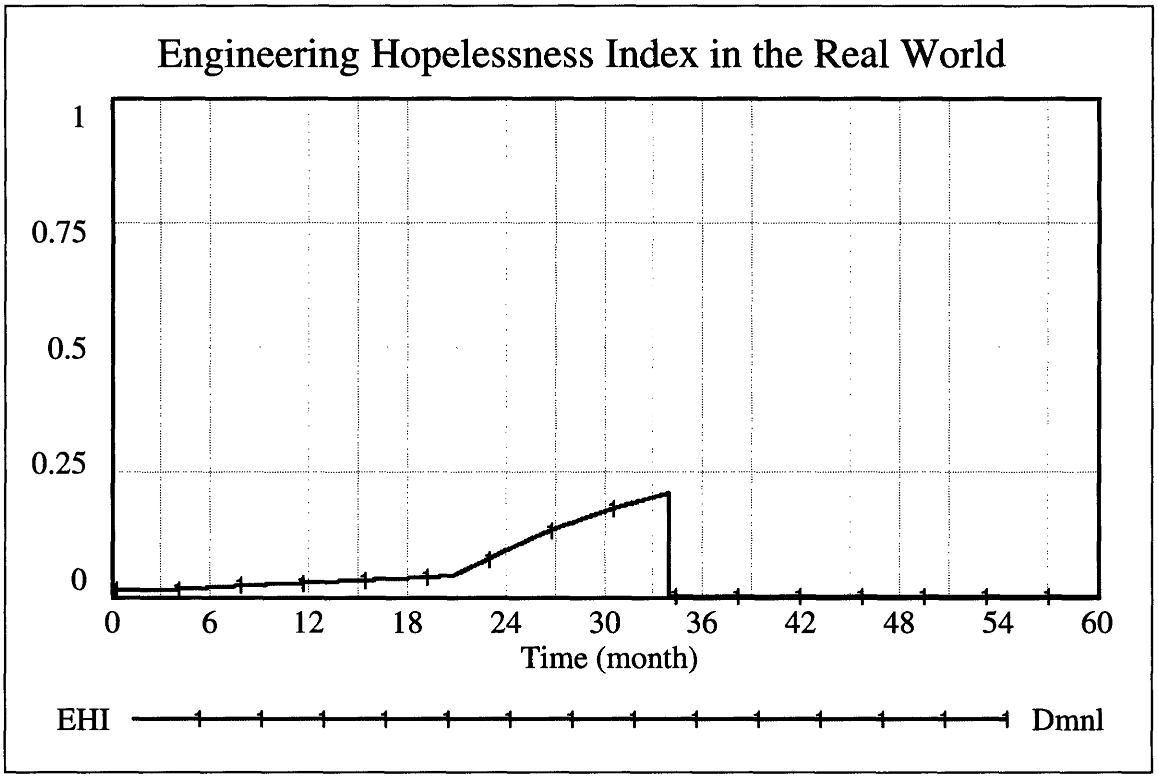


Figure 94. EHI in a Real World

The engineers start along a slope of increasing "hopelessness" which continues to grow throughout the duration of the project. At about 20 months in, the project is less than 50% complete with a serious cash deficit, and abysmal profit numbers. The rate of schedule pressure increase begins to accelerate, leading to additional quality problems requiring rework and ultimately a more rapidly declining budget performance which results in more rapid growth of the EHI.

5.3.4.4 In the Real World: Sensitivity of Effect of Schedule Pressure on Willingness to Accept Interruptions

The following factors are plotted, over time, for sensitivity simulations of the real world scenario:

- **Effect of Schedule Pressure on Willingness to Accept Interruptions**

- **Effect of Schedule Pressure on Cash**
- **Effect of Schedule Pressure on Profit**
- **Effect of Schedule Pressure on EPI**
- **Effect of Schedule Pressure on EPSQ**
- **Effect of Schedule Pressure on EHI**

A 50% decrease in schedule pressure sensitivity and a 175% increase in schedule pressure sensitivity was simulated to see how engineering response to schedule pressure effects the behavior of the system. These output plots are provided in Figures 95-100 below.

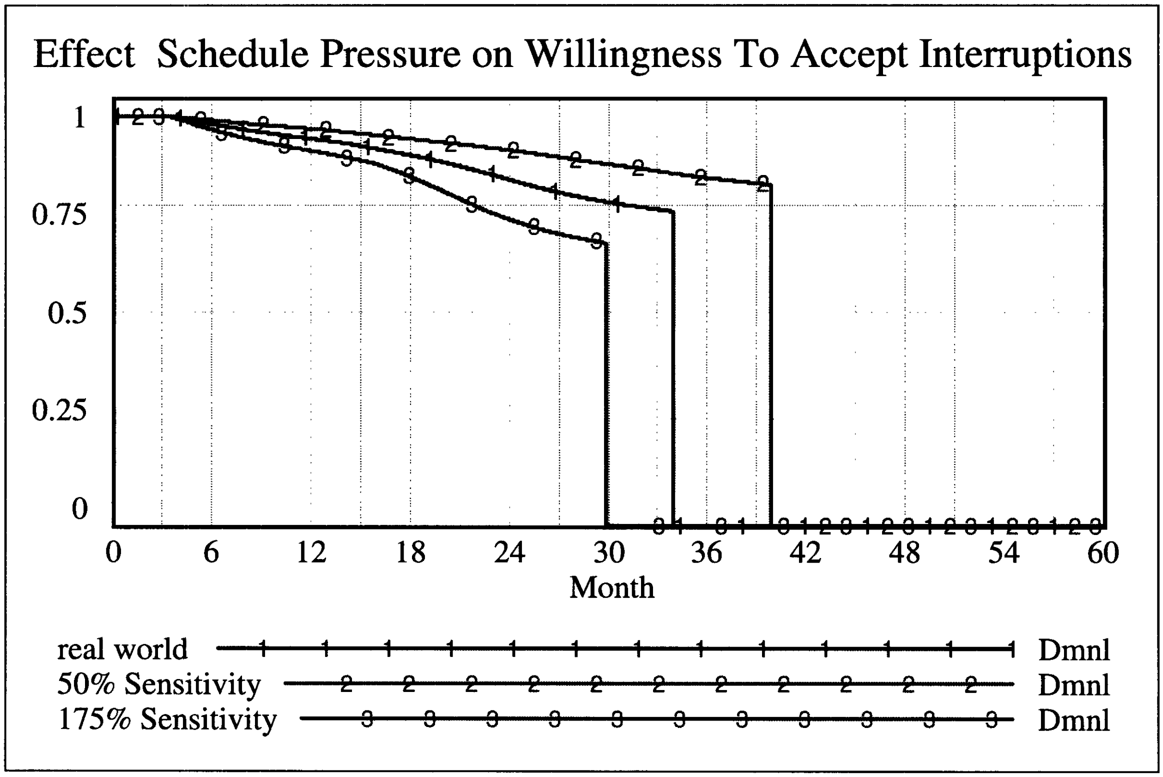


Figure 95. Sensitivity of Schedule Pressure on Willingness to Accept Interruptions

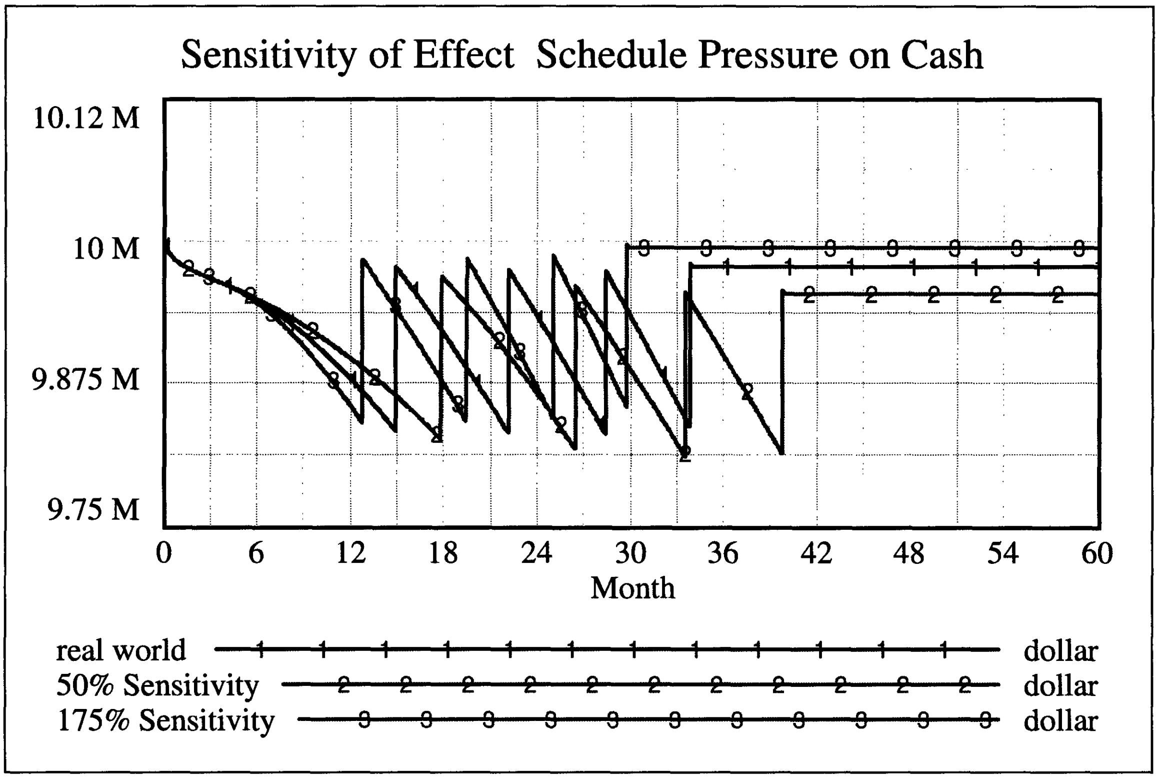


Figure 96. Sensitivity of Schedule Pressure on Cash Performance

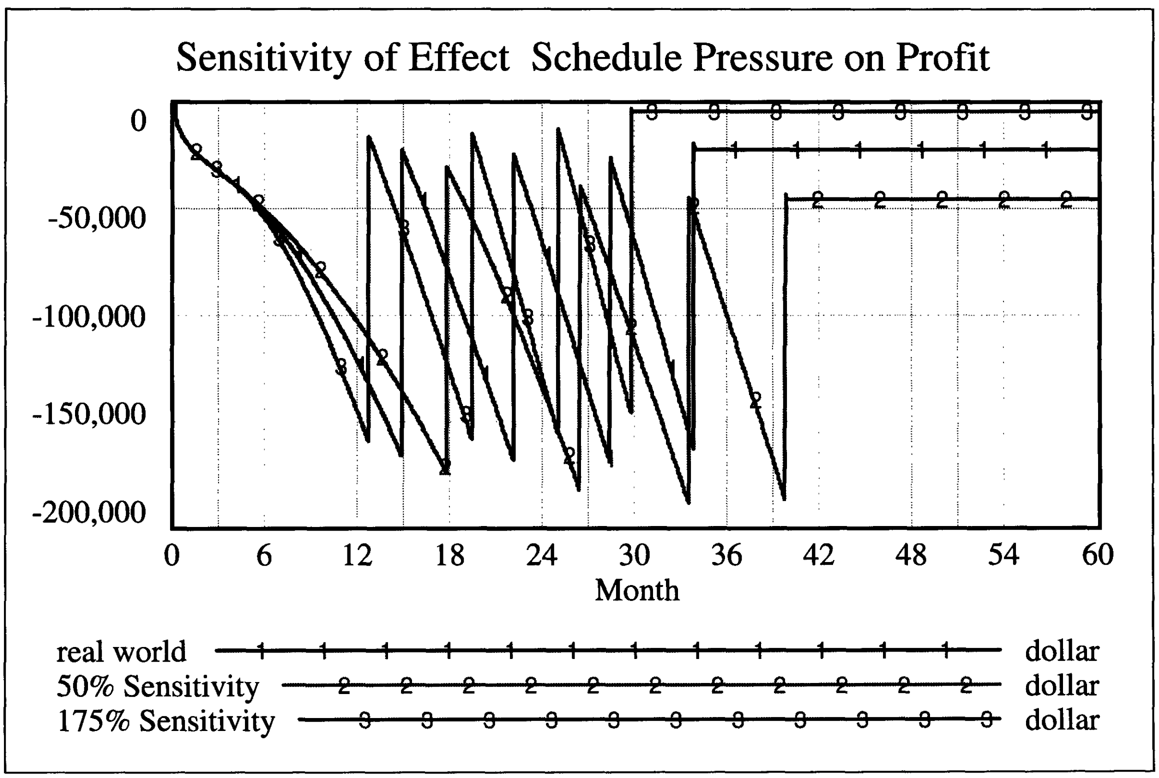


Figure 97. Sensitivity of Schedule Pressure on Profit Performance

As the engineers become "more sensitive" to schedule pressure, they begin to refuse more and more interruptions allowing them to preserve productivity levels. This is clear from the measures of cash and profit above in Figures 96 & 97. As a result, EPI can be improved as sensitivity to schedule pressure is increased as indicated in Figure 98 below.

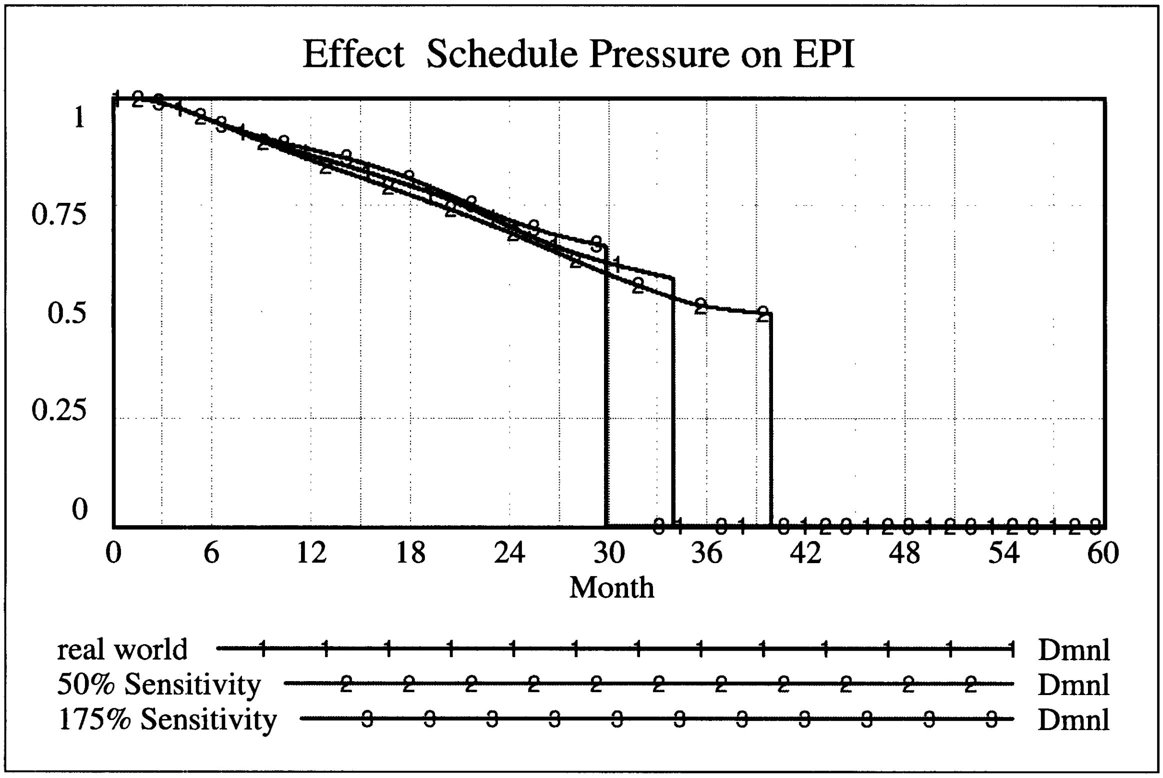


Figure 98. Sensitivity of Schedule Pressure on EPI

However, this increased sensitivity to schedule pressure also results in the perceived service quality of the engineering department declining as indicated in Figure 99 below. This is because the performance indices of other interfacing groups are likely to be affected negatively by lack of engineering support.

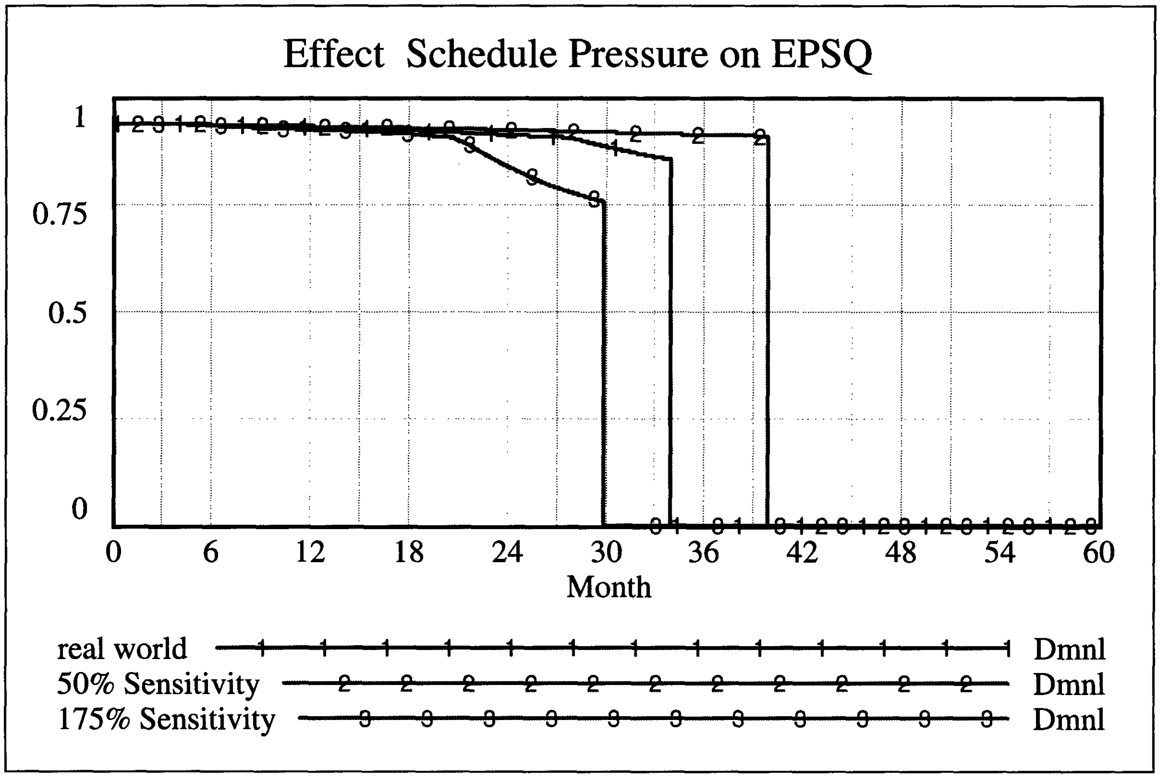


Figure 99. Sensitivity of Schedule Pressure on EPSQ

Figure 100 below indicates that even with a drop in service quality levels, the hopelessness index is still reduced overall with an increased sensitivity to schedule pressure. This points to an interesting possibility that engineers may be more heavily influenced by the service quality parameters than the on time, under budget, and right-the-first-time parameters, perhaps as a result of the organizational culture as well as the strong and immediate feedback cues resulting from turning away someone in need, vs. a periodic admonishment from program management that the project is way off track.

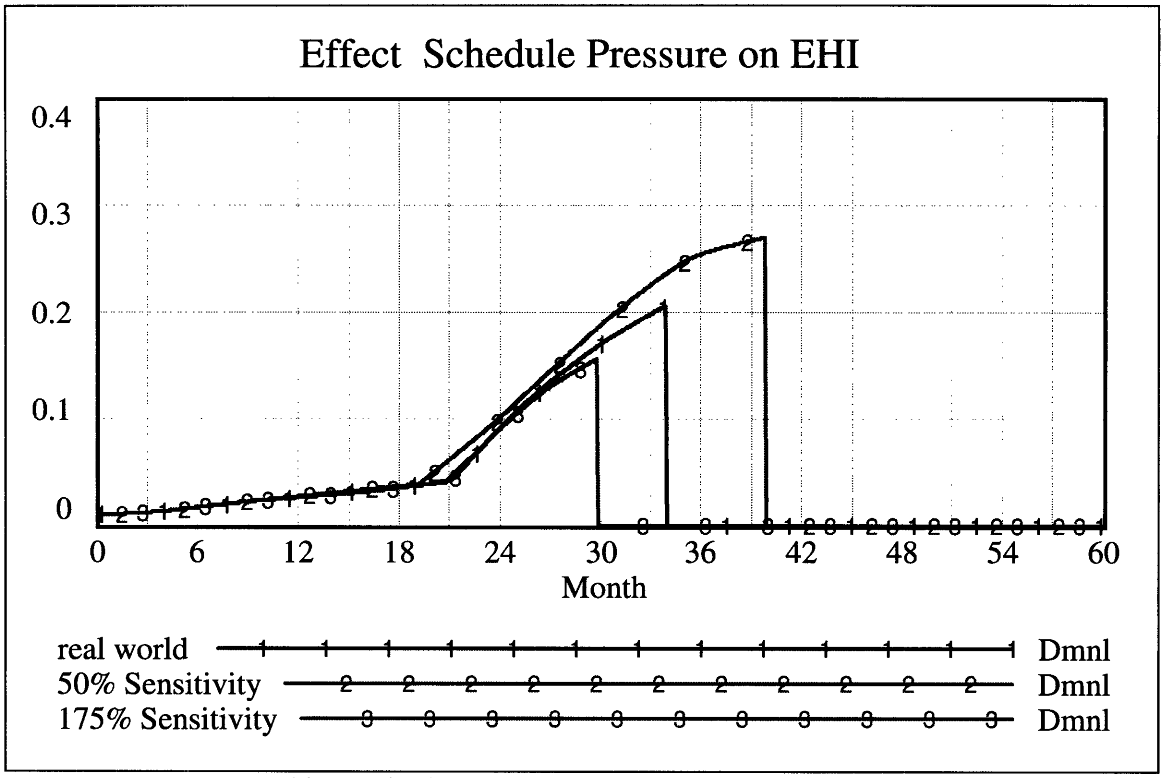


Figure 100. Sensitivity of Schedule Pressure on EHI

6.0 DISCUSSION

The results of the research efforts described above demonstrate the significant impacts that interruptions have on engineering project task performance. As the willingness to accept interruptions increases, the effective amounts of resources that are dedicated to task completion are reduced. This reduction in resources affects the rate at which project work can be accomplished. Furthermore, the work rate is further diminished as a cognitive "reset" penalty is incurred every time an engineer is interrupted. The reduction in work rate causes the project to be delayed, having a significant impact on cash flow for the project. The project delays result in increasing schedule pressure. The schedule pressure has a negative impact on the ability to accomplish tasks correctly and causes an increase in required rework, which upon discovery, leads to increasing costs and budget overruns. A regulating effect exists in that the increasing schedule pressure reduces the tendency of engineers to accept interruptions as a means to preserve productivity, and the good will of the program managers. However, as engineers become less willing to accept interruptions, the impacts to other groups within the organization begin to mount. The other groups begin to suffer the same types of effects of schedule pressure and resulting quality degradation when critical information is not provided in a timely fashion by engineering. When this occurs, there is an escalation to higher power/influence levels in the other groups resulting in an increase in rank for a new interruption requesting the information previously sought. This has the effect of counteracting the schedule pressure self-preservation mechanism. In addition, when escalation occurs, the perception of the engineering group as a service provider is degraded. In the aggregate, the cost/schedule performance, the task execution quality, and the service quality perceptions of the rest of the organization combine to reinforce a message of inadequacy and futility for improvements in long term engineering capability and performance.

One very interesting result, borne out by the sensitivity simulations, is that the focus on service quality may have some counter intuitive effects, or at a minimum, result in sub-optimization. As the sensitivity of schedule pressure is increased, there is a commensurate decrease in perceived engineering service quality level. However, there is a larger improvement in engineering performance index that serves to reduce the ultimate hopelessness index. This confirms the intuition that there is a tradeoff between service quality level and project performance.

Although the modeling and simulation results focus on the engineering task execution process, they imply some significant impacts to the rest of the organization as well. Although there may be an optimum policy for the individuals within the engineering group, that allows them to maximize the performance and service quality perceptions effectively, there is likely to be effects on other groups within the organization because of the central role played by engineering as a source of significant information and knowledge, as evidenced by network analyses conducted as part of this research. The comment made during one of the interviews about being the "light at the head of the train" succinctly identifies the prominent, central, and critical role of the engineers within fundamental business processes. This suggests that to effectively address interruptions requires a "systems view" that seeks to balance the effects of policy changes in engineering with effects in the rest of the organization. It makes little sense to optimize project task execution in engineering if the resulting impacts to aggregate business profit and cash, which include contributions from sales/marketing, production, aftermarket, etc. are negative.

The research also indicates that the concentration of knowledge within the engineering department may be a contributing factor to the structure and resulting behavior of the system as well. If knowledge was more easily accessible, or more widely held, there would be less need for interruptions to project task execution. This has implications for the qualifications held by, and the training programs conducted in the rest of the organization outside of engineering, as one interview respondent put it, "to [more effectively] arm the front [and back] end of the business" In order to facilitate this spread of knowledge, commitments to formalized training and/or incentives and motivations for other groups to acquire knowledge, sufficient to make decisions without the support of the engineering department. Without such mechanisms, the concentration of knowledge in engineering intensifies, decreasing the satisfaction of all stakeholders.

7.0 FUTURE WORK

Although the current research has been successful in meeting its objectives, there is opportunity for significant additional work providing further insights into interruption management, as well as the effect of engineering project task execution performance on the rest of the organization. The following areas are suggested for further research:

1) Further calibration of the system dynamics model with data from previous projects
2) Additional sensitivity analyses considering alternative interruption management policies
3) Use of the CLD's developed as part of this research to expand the model to include explicit impacts on other groups within the organization
4) Implementation of discrete interruption frequency and duration to assess the impacts of particular types of interruptions

There are likely several other potential areas of research that may provide meaningful insights, or implications for business process improvements.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions/recommendations are made based on the results of this research:

1) Engineering holds a central role as a provider of critical information to other groups within the organization. The degree to which Engineering is a required resource for other groups is, on average, much higher than the degree to which other groups are a required resource of engineering, especially with regards to engineering project task execution process.
2) Interruptions have a significant impact on the cost/schedule performance of a project, as well as the perceptions (external and self) of engineering as an effective member of the business "team".
3) The focus on perceived service quality, which can be a fundamental component of corporate culture and philosophy, may serve to counteract the schedule pressure self-preservation mechanism inherent in the current interruption management policy
4) Optimization of the engineering interruption management policies may not result in improvements to the aggregate business performance indicators because of the feedback mechanisms and cause-effect linkages that exist between the engineering department and the other groups within the team. As such, a systems approach is recommended, whereby the larger system is treated explicitly.
5) Knowledge concentration in engineering has a significant impact on the structure of the business system. Through the spread of knowledge, there is a possibility for structural

modifications, and behavior policies to be changed such that the entire organization can operate more effectively. This will likely require careful examination of formal training programs, and incentives for knowledge sharing and accumulation.

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APPENDIX A – SYSTEM DYNAMICS MODEL EQUATION LISTING

Following is an equation listing of the formal system dynamics model that was developed and ustilized as part of the current research effort. The equations were exported from the model using the Vensim© model documentation function.

EQUATION LISTING:

```
(001) accummulation rate=rework identification rate
      Units: task/month

(002) actual project resources available=allocated project resources*(1-
diversion fraction)
      Units: person

(003) allocated project resources= INTEG (allocation and deallocation rate,
initially allocated resources)
      Units: person

(004) allocation and deallocation rate= nominal allocation rate
      Units: person/month

(005) anticipated schedule overrun= ((perceived real completion date-
scheduled completion date)/scheduled completion date)*project finished
      Units: Dimensionless

(006) average productivity=IF THEN ELSE (cummulative effort
expended>0:OR:project tasks completed>1, real productivity*(work believed to
be done/cummulative effort expended)* (cummulative effort expended/work
believed to be done),real productivity)
      Units: task/(month*person)

(007) budgeted actual project resources available=allocated project
resources*(1-budgeted diversion fraction)
      Units: person

(008) budgeted cash burn rate= budgeted actual project resources
available*resource cost*budgeted project finished
      Units: dollar/month

(009) budgeted cost to complete= ((project tasks to do)/normal
productivity)*(1-fraction perceived to be complete)
      Units: month*person

(010) budgeted diversion fraction=IF THEN ELSE(perfect world switch, 0,
normal diversion fraction)
      Units: Dmnl
```

(011) budgeted normal work rate=budgeted actual project resources available*budgeted real productivity
      Units: task/month

(012) budgeted percent task completion=budgeted project tasks completed/initial project tasks to do
      Units: Dmnl

(013) budgeted project cost=500000
      Units: dollar

(014) budgeted project finished=IF THEN ELSE(budgeted project tasks completed/initial project tasks to do>=0.995,0, 1)
      Units: Dmnl

(015) budgeted project tasks completed= INTEG (budgeted task completion rate, 0)
      Units: task
      current (successfully) completed project tasks

(016) budgeted project tasks to do= INTEG (+budgeted rework identification rate-budgeted rework generation rate-budgeted task completion rate, initial project tasks to do)
      Units: task
      current number of tasks to be completed

(017) budgeted real productivity=IF THEN ELSE(perfect world switch, 4, normal productivity)
      Units: task/(person*month)

(018) budgeted real quality=IF THEN ELSE(perfect world switch, 1, normal quality)
      Units: Dmnl

(019) budgeted rework generation rate=budgeted normal work rate*(1-budgeted real quality)*budgeted project finished
      Units: task/month
      rate at which rework is generated

(020) budgeted rework identification rate="budgeted un-discovered rework"/budgeted time to discover rework*budgeted project finished
      Units: task/month
      rework identification rate

(021) budgeted task completion rate=budgeted normal work rate*budgeted real quality*budgeted project finished
      Units: task/month
      rate at which tasks are completed

(022) budgeted time to discover rework=0.5
      Units: month
      time to discover rework

(023) "budgeted un-discovered rework"= INTEG (budgeted rework generation rate-budgeted rework identification rate, 0)
      Units: task

current number of undiscovered rework tasks

(024) cash= INTEG (inflow-outflow, initial cash position)
Units: dollar

(025) cash burn rate=actual project resources available*resource cost*project finished
Units: dollar/month

(026) cash forecast= INTEG (inflow forecast-outflow forecast, initial cash position)
Units: dollar

(027) cummulative effort expended= INTEG (effort, 0)
Units: month*person

(028) cummulative identified rework= INTEG (accummulation rate, 0)
Units: task

(029) current profit margin=profit/budgeted project cost
Units: Dmnl

(030) current profit margin forecast=profit forecast/budgeted project cost
Units: Dmnl

(031) customer focus of resource=0.8
Units: Dmnl

(032) desired profit margin=0.15
Units: Dmnl

(033) diversion fraction=interruption switch*IF THEN ELSE(perfect world switch, normal diversion fraction, MIN(normal diversion fraction+sensitivity of willingess to accept interruption*effect of willingness to accept interruption on diversion fraction (willingness to accept interruption)+(1-sensitivity of willingess to accept interruption),1))
Units: Dmnl

(034) effect of anticipated overrun on schedule pressure([(-1,0)-(10,2)],(-1,0),(0,0),(0.5,0.25),(1,0.5),(2,0.95),(10,0.95))
Units: Dmnl

(035) effect of cost performance on underbudget factor([(0,0)-(6,1)],(0,1),(1,1),(3,0),(6,0))
Units: Dmnl

(036) effect of customer focus on willingness to accept interruption([(0,0)-(1,1)],(0,0),(0.125,0.375),(0.25,0.625),(0.5,0.875),(1,1))
Units: Dmnl

(037) effect of diversion fraction on productivity penalty([(0,0)-(1,1)],(0,1),(0.237647,0.957295),(0.498824,0.886121),(0.712941,0.772242),(0.884706,0.551601),(1,0))
Units: Dmnl

(038) effect of duration on willingness to accept interruption([(0,0)-(1,1)],(0,1),(0.025,1),(0.05,0),(1,0))

Units: Dmnl

(039) effect of EPI on hopelessness([(0,0)-
(1,1)],(0,1),(0.247059,0.943061),(0.494118,0.508897),(0.755294,0.0533808),(1,
0))
Units: Dmnl

(040) effect of EPSQ on hoplessness([(0,0)-
(1,1)],(0,1),(0.242353,0.896797),(0.489412,0.512456),(0.748235,0.0818505),(1,
0))
Units: Dmnl

(041) effect of immediacy on willingness to accept interruption([(0,0)-
(1,1)],(0,0),(0.25,0.0625),(0.5,0.1875),(0.75,0.5),(0.875,1),(1,1))
Units: Dmnl

(042) effect of interrupter schedule pressure on perceived immediacy([(0,0)-
(1,1)],(0,0),(0.254118,0.0818505),(0.407059,0.231317),(0.501176,0.483986),(0.
630588,0.80427),(0.752941,0.996441),(1,1))
Units: Dimensionless

(043) effect of interruptor schedule pressure on perceived service quality(
[(0,0)-(1,1)],(0,1),(0.247059,1),(0.494118,1),(0.750588,0.05),(1,0))
Units: Dmnl

(044) effect of interruptor schedule pressure on time to update service
quality perception ([(0,0)-
(1,1)],(0,1),(0.247059,0.950178),(0.498824,0.782918),
(0.736471,0.508897),(1,0.1))
Units: month

(045) effect of perceived immediacy on time to escalate rank([(0,0)-
(1,4)],(0,3),(0.247059,2.76157),(0.498824,2.37722),(0.748235,1.75),(0.865882,
0.25),(0.943529,0.025),(1,0.025))
Units: month

(046) effect of reciprocity on willingness to accept interruption([(0,0)-
(1,1)],(0,0),(0.5,1),(1,1))
Units: Dmnl

(047) effect of rework fraction on right the first time factor([(0,0)-
(1,1)],(0,1),(0.25,0.5),(0.5,0),(1,0))
Units: Dmnl

(048) "effect of schedule overrun on on-time factor"([(0,0)-
(40,1)],(0,1),(1.12941,0.679715),(3.10588,0.330961),(4.32941,0.174377),(7.058
82,0.103203),(10.5412,0.0711744),(14.6824,0.0391459),(19.8588,0.0177936),(30,
0),(40,0))
Units: Dmnl

(049) effect of schedule pressure on quality([(0,0)-
(1,1)],(0,1),(0.1,0.975),(0.2,0.93),(0.3,0.87),(0.4,0.8),(0.5,0.736655),(0.59
5294,0.686833),(0.705882,0.622776),(1,0.5))
Units: Dmnl

(050) effect of schedule pressure on willingness to accept interruption(
[(0,0)-

(1,1)],(0,1),(0.258824,0.921708),(0.498824,0.818505),(0.738824,0.697509),(0.898823,0.587189),(0.969412,0.409253),(1,0.2))
Units: Dmnl

(051) effect of willingness to accept interruption on diversion fraction([(0,0)-(1,1)],(0,0),(0.25,0.0320285),(0.583529,0.0925267),(0.875294,0.25),(0.96,0.4375),(1,0.65))
Units: Dmnl

(052) effect of willingness to accept interruption on interrupter schedule pressure ([(0,0)-(1,1)],(0,1),(0.136471,1),(0.242353,0.975089),(0.362353,0.928826),(0.456471,0.825623),(0.531765,0.690391),(0.628235,0.572954), (0.776471,0.519573),(1,0.508897))
Units: Dimensionless

(053) effort=allocated project resources*project finished
Units: person

(054) engineering cost performance= (cummulative effort expended+estimated cost to complete)*resource cost/budgeted project cost
Units: Dmnl

(055) Engineering Hopelessness Index= (0.5*effect of EPSQ on hoplessness(Engineering Perceived Service Quality) +0.5*effect of EPI on hopelessness(Engineering Performance Index))*project finished
Units: Dmnl

(056) Engineering Perceived Service Quality=project finished*SMOOTH(effect of interruptor schedule pressure on perceived service quality (interrupter schedule pressure), time to update engineering service quality perception)
Units: Dmnl

(057) Engineering Performance Index=project finished*SMOOTH(weighted performance factor, time to update engineering performance perception)
Units: Dmnl

(058) estimated cost to complete=budgeted cost to complete*(1-weight on progress based estimates)+(estimated cost to complete based on progress)*weight on progress based estimates
Units: month*person

(059) estimated cost to complete based on progress= (project tasks to do/average productivity)*project finished
Units: month*person

(060) expected relative rank of interruption=SMOOTHI(interrupter perceived immediacy of interruption, time to escalate rank, 0.5)
Units: Dmnl

(067) FINAL TIME = 60
Units: month
The final time for the simulation.

(068) fraction perceived to be complete=work believed to be done/initial project tasks to do
Units: Dmnl

(069) indicated completion date based on progress= (Time+(estimated cost to complete/MAX(0.0001,allocated project resources)))*project finished
Units: month

(070) inflow= (budgeted project cost*(1+desired profit margin) /number of milestones)* (invoice trigger A is on+invoice trigger B is on+invoice trigger C is on +invoice trigger D is on)/TIME STEP
Units: dollar/month

(071) inflow forecast= (budgeted project cost*(1+desired profit margin/number of milestones)* (invoice trigger A2 is on+invoice trigger B2 is on+invoice trigger C2 is on+invoice trigger D2 is on)/TIME STEP
Units: dollar/month

(072) initial cash position=1e+007
Units: dollar

(073) initial project tasks to do=100
Units: task
inital number of project tasks to be done

(074) INITIAL TIME = 0
Units: month
The initial time for the simulation.

(075) initially allocated resources=2
Units: person

(076) interrupter perceived immediacy of interruption=effect of interrupter schedule pressure on perceived immediacy(interrupter schedule pressure)
Units: Dmnl

(077) interrupter schedule pressure=sensitivity of willingness on interruptor schedule pressure*effect of willingness to accept interruption on interrupter schedule pressure (willingness to accept interruption)+(1-sensitivity of willingness on interruptor schedule pressure)
Units: Dimensionless

(080) interruption switch=1
Units: Dmnl

(082) invoice trigger A is on=IF THEN ELSE(project finished=0:OR:milestone switch A<4, 0, IF THEN ELSE(percent task completion>=0.25:AND: invoice trigger A was on=0 , 1, 0))
Units: Dmnl

(083) invoice trigger A was on=DELAY FIXED(invoice trigger A is on, 0, 0)
Units: Dmnl

(084) invoice trigger A2 is on=IF THEN ELSE(budgeted project finished=0:OR:milestone switch A2<4, 0, IF THEN ELSE (budgeted percent task completion>=0.25:AND: invoice trigger A2 was on=0 , 1, 0))
Units: Dmnl

(085) invoice trigger A2 was on=DELAY FIXED(invoice trigger A2 is on, 0, 0)
Units: Dmnl

(086) invoice trigger B is on=IF THEN ELSE(project finished=0:OR:milestone switch B<3, 0, IF THEN ELSE(percent task completion>=0.5:AND: invoice trigger B was on=0 , 1, 0))
Units: Dmnl

(087) invoice trigger B was on=DELAY FIXED(invoice trigger B is on, 0, 0)
Units: Dmnl

(088) invoice trigger B2 is on=IF THEN ELSE(budgeted project finished=0:OR:milestone switch B2<3, 0, IF THEN ELSE (budgeted percent task completion>=0.5:AND: invoice trigger B2 was on=0 , 1, 0))
Units: Dmnl

(089) invoice trigger B2 was on=DELAY FIXED(invoice trigger B2 is on, 0, 0)
Units: Dmnl

(090) invoice trigger C is on=IF THEN ELSE(project finished=0:OR:milestone switch C<3, 0, IF THEN ELSE(percent task completion>=0.75:AND: invoice trigger C was on=0 , 1, 0))
Units: Dmnl

(091) invoice trigger C was on=DELAY FIXED(invoice trigger C is on, 0, 0)
Units: Dmnl

(092) invoice trigger C2 is on=IF THEN ELSE(budgeted project finished=0:OR:milestone switch C2<3, 0, IF THEN ELSE (budgeted percent task completion>=0.75:AND: invoice trigger C2 was on=0 , 1, 0))
Units: Dmnl

(093) invoice trigger C2 was on=DELAY FIXED(invoice trigger C2 is on, 0, 0)
Units: Dmnl

(094) invoice trigger D is on=IF THEN ELSE(project finished=0:OR:milestone switch D<3, 0, IF THEN ELSE(percent task completion>=0.99:AND: invoice trigger D was on=0 , 1, 0))
Units: Dmnl

(095) invoice trigger D was on=DELAY FIXED(invoice trigger D is on, 0, 0)
Units: Dmnl

(096) invoice trigger D2 is on=IF THEN ELSE(budgeted project finished=0:OR:milestone switch D2<3, 0, IF THEN ELSE (budgeted percent task completion>=0.99:AND: invoice trigger D2 was on=0 , 1, 0))
Units: Dmnl

(097) invoice trigger D2 was on=DELAY FIXED(invoice trigger D2 is on, 0, 0)
Units: Dmnl

(098) milestone switch A=SMOOTHI(invoice trigger A is on, TIME STEP/2, number of milestones)
Units: Dmnl

(099) milestone switch A2=SMOOTHI(invoice trigger A2 is on, TIME STEP/2, number of milestones)
Units: Dmnl

(100) milestone switch B=SMOOTHI(invoice trigger B is on, TIME STEP/2, number of milestones)
Units: Dmnl

(101) milestone switch B2=SMOOTHI(invoice trigger B2 is on, TIME STEP/2, number of milestones)
Units: Dmnl

(102) milestone switch C=SMOOTHI(invoice trigger C is on, TIME STEP/2, number of milestones)
Units: Dmnl

(103) milestone switch C2=SMOOTHI(invoice trigger C2 is on, TIME STEP/2, number of milestones)
Units: Dmnl

(104) milestone switch D=SMOOTHI(invoice trigger D is on, TIME STEP/2,number of milestones)
Units: Dmnl

(105) milestone switch D2=SMOOTHI(invoice trigger D2 is on, TIME STEP/2, number of milestones)
Units: Dmnl

(118) nominal allocation rate=0
Units: person/month

(119) normal diversion fraction=0.05
Units: Dmnl

(120) normal productivity=4
Units: task/(month*person)

(121) normal quality=0.95
Units: Dmnl

(122) normal work rate=actual project resources available*real productivity
Units: task/month

(123) number of milestones=4
Units: Dmnl

(124) "on-time factor"="effect of schedule overrun on on-time factor"(anticipated schedule overrun)
Units: Dmnl

(125) outflow=cash burn rate
Units: dollar/month

(126) outflow forecast=budgeted cash burn rate
Units: dollar/month

(127) perceived future reciprocity=0.5
Units: Dmnl

(128) perceived immediacy of interruption=0.5
Units: Dmnl

(129) perceived real completion date=SMOOTHI(indicated completion date based on progress,time to perceive real schedule,scheduled completion date)*project finished
Units: month

(130) percent task completion=project tasks completed/initial project tasks to do
Units: Dmnl

(131) perfect world switch=0
Units: Dmnl

(132) predicted interruption duration=0.01
Units: Dmnl

(133) productivity penalty due to diversions=effect of diversion fraction on productivity penalty(diversion fraction)
Units: Dmnl

(134) profit=cash-initial cash position
Units: dollar

(135) profit forecast=cash forecast-initial cash position
Units: dollar

(136) project finished=IF THEN ELSE(project tasks completed/initial project tasks to do>=0.995,0 , 1)
Units: Dmnl

(137) project tasks completed= INTEG (task completion rate, 0)
Units: task
current (successfully) completed project tasks

(138) project tasks to do= INTEG (+rework identification rate-rework generation rate-task completion rate, initial project tasks to do)
Units: task

(159) real productivity=IF THEN ELSE(perfect world switch=1, 4, normal productivity*productivity penalty due to diversions)
Units: task/(person*month)

(160) real quality=IF THEN ELSE(perfect world switch=1, 1, normal quality*effect of schedule pressure on quality (schedule pressure)*sensitivity of schedule pressure on quality+(1-sensitivity of schedule pressure on quality))
Units: Dmnl

(161) resource cost=125*8*20
Units: dollar/(person*month)
$125 dollars/hour, 8 hours/day, 20 working days/month

(162) rework fraction=cummulative identified rework/initial project tasks to do
Units: Dmnl

(163) rework generation rate=normal work rate*(1-real quality)*project finished
Units: task/month
rate at which rework is generated

(164) rework identification rate="un-discovered rework"/time to discover rework*project finished
Units: task/month
rework identification rate

(165) "right-the-first-time factor"=effect of rework fraction on right the first time factor(rework fraction)
Units: Dmnl

(166) SAVEPER = TIME STEP
Units: month .
The frequency with which output is stored.

(167) schedule pressure=effect of anticipated overrun on schedule pressure(anticipated schedule overrun)
Units: Dmnl

(168) scheduled completion date=initial project tasks to do/(allocated project resources*(1-normal diversion fraction)*normal productivity*normal quality)
Units: month

(169) sensitivity of perceived immediacy on escalation=1
Units: Dmnl

(170) sensitivity of schedule pressure on quality=0.15
Units: Dmnl

(171) sensitivity of schedule pressure on willingness=1.75
Units: Dimensionless

(172) sensitivity of willingess to accept interruption=0.1
Units: Dmnl

(173) sensitivity of willingness on interruptor schedule pressure=1
Units: Dmnl

(189) table for weight on progress based estimates([(0,0)-(1,1)],(0,0),(0.1,0),(0.2,0),(0.3,0.1),(0.4,0.25),(0.5,0.5),(0.6,0.75),(0.7,0.9),(0.8,1),(0.9,1),(1,1))
Units: Dmnl

(190) task completion rate=normal work rate*real quality*project finished
Units: task/month
rate at which tasks are completed

(191) TIME STEP = 0.03125
Units: month
The time step for the simulation.

(192) time to discover rework=0.5
Units: month

time to discover rework

(193) time to escalate rank=sensitivity of perceived immediacy on escalation*effect of perceived immediacy on time to escalate rank (interrupter perceived immediacy of interruption)
Units: month

(194) time to perceive real schedule=1
Units: month

(195) time to update engineering performance perception=1
Units: month

(196) time to update engineering service quality perception=effect of interruptor schedule pressure on time to update service quality perception (interrupter schedule pressure)
Units: month

(197) "un-discovered rework"= INTEG (rework generation rate-rework identification rate, 0)
Units: task
current number of undiscovered rework tasks

(198) "under-budget factor"=effect of cost performance on underbudget factor(engineering cost performance)
Units: Dmnl

(199) weight on progress based estimates=table for weight on progress based estimates(fraction perceived to be complete)
Units: Dmnl

(200) weighted performance factor=0.33*"on-time factor"+0.33*"under-budget factor"+0.34*"right-the-first-time factor"
Units: Dmnl

(201) willingness to accept interruption=project finished*IF THEN ELSE(expected relative rank of interruption>1, 1 , (0.8*(sensitivity of schedule pressure on willingness*effect of schedule pressure on willingness to accept interruption (schedule pressure)+(1-sensitivity of schedule pressure on willingness))+ 0.05*effect of customer focus on willingness to accept interruption(customer focus of resource)+0.05*effect of duration on willingness to accept interruption (predicted interruption duration)+0.05*effect of immediacy on willingness to accept interruption (perceived immediacy of interruption)+0.05*effect of reciprocity on willingness to accept interruption(perceived future reciprocity)))
Units: Dmnl

(202) work believed to be done=project tasks completed+"un-discovered rework"
Units: task